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OF WASTE SULFATE
REMEDIAL TREATMENT OF SOILS

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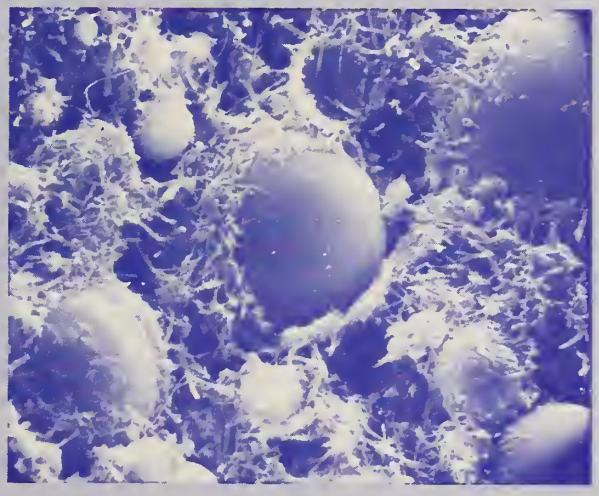

August 1976
Final Report

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FOREWORD

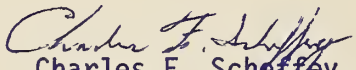
This report presents the results of a laboratory study to evaluate the effects of sulfate waste on the engineering properties of fine-grained soils. The report will be of interest to materials, soils and pavement design engineers in addition to other researchers concerned with soil stabilization for pavements and earth structures.

The results were developed under Midwest Research Institute, Project 3960-C, conducted for the Federal Highway Administration, Office of Research, Washington, D.C., under Contract DOT-FH-11-8515. This final report covers the period of research from September 1, 1974, to September 30, 1976.

Other persons contributing to the program were: Mr. John Sealock, Associate Chemist; Mr. Mark Valentine, Associate Environmental Engineer; and Mr. Kenneth Walker, Assistant Chemist. Dr. Ramesh C. Jashi of Woodward-Clyde Consultants, Central Region, Kansas City, Missouri, served as a consultant in the soil testing aspects of the program.

The authors wish to specially acknowledge the cooperation of the Soil Survey Interpretation Division, Soil Conservation Service, U.S. Department of Agriculture, Dr. Lindo J. Bartelli, Director. Dr. Don McCormack of the Washington staff coordinated efforts among SCS field personnel to enable the identification and acquisition of soil samples used in this study. The SCS field personnel involved are: Maurice Stout, Jr., Midwest Technical Service Center, Lincoln, Nebraska; John D. Roarke, Northeast Technical Service Center, Upper Darby, Pennsylvania; and James R. Coover, Southern Technical Service Center, Fort Worth, Texas.

Copies of the report are being distributed by the Materials Division, Office of Research, to the FCP Project 4C team and appropriate members of the FCP Project 4D team.



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15. Supplementary Notes

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16. Abstract

The effects of waste sulfate (phosphogypsum from fertilizer manufacture, flue gas desulfurization solids, and neutralized acid mine drainage solids) on physical and strength properties of soils have been studied. Waste sulfate alone has little effect on soil strengths. However, if it is used in combination with lime, higher strengths can be achieved with waste sulfate/lime than can be obtained with equivalent lime treatment because of soil-sulfate-lime reactions. Fly ash can be used with waste sulfate/lime mixtures to improve strengths further. Cement kiln dust has been shown to be an effective substitute for lime as a soil stabilizer.

The report is presented in two volumes. Volume I--Discussion of Results--describes the experimental work and contains the interpretation of data and conclusions and recommendations. Volume II--Appendixes--contains an annotated bibliography of literature reviewed, Atterberg Limit and moisture-density data for waste sulfate/soil systems, experimental unconfined compressive strength data, and an outline of multiple regression procedures used for data analysis.

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PREFACE

This document contains the final report concerning "Use of Waste Sulfate for Remedial Treatment of Soils," conducted for the U.S. Department of Transportation, Federal Highway Administration, under Contract No. DOT-FH-11-8515.

The principal investigator of this program has been Dr. John W. Nebgen, Principal Chemist. He has been assisted by Mr. James G. Edwards, Assistant Chemist; Mr. Douglas F. Weatherman, Assistant Chemist; and Mr. J. Kevin Cline, Technician. These three persons were responsible for the experimental work, program scheduling, and data reduction. Administrative and technical supervision of the program was provided by Dr. A. D. McElroy, Head, Treatment and Control Processes Section.

Other persons contributing to the program were: Mr. John Sealock, Associate Chemist; Mr. Mark Valentine, Associate Environmental Engineer; and Mr. Kenneth Walker, Assistant Chemist. Dr. Ramesh C. Joshi of Woodward-Clyde Consultants, Central Region, Kansas City, Missouri, served as a consultant in the soils testing aspects of the program.

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The authors wish to specially acknowledge the cooperation of the Soil Survey Interpretation Division, Soil Conservation Service, U.S. Department of Agriculture, Dr. Lindo J. Bartelli, Director. Dr. Don McCormack of the Washington staff coordinated efforts among SCS field personnel to enable the identification and acquisition of soil samples used in this study. The SCS field personnel involved were: Maurice Stout, Jr., Midwest Technical Service Center, Lincoln, Nebraska; John D. Roarke, Northeast Technical Service Center, Upper Darby, Pennsylvania; and James R. Coover, Southern Technical Service Center, Fort Worth, Texas.

Approved for:

MIDWEST RESEARCH INSTITUTE

L. J. Shannon, Director
Environmental and Materials Sciences
Division

November 4, 1976

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I. INTRODUCTION

A laboratory study has been conducted to determine the effects of adding sulfate waste to soils on mechanical properties of the soils. The purpose of the program was to establish the broad parameters associated with waste sulfate and waste sulfate/lime mixtures as soil stabilization agents. It has been determined that waste sulfate/lime mixtures are excellent soil stabilization agents, and that waste sulfate also can be added to soils without adversely affecting engineering properties in most cases. Results of the laboratory experiments and data analysis leading to these conclusions are detailed in later sections of this report.

Waste sulfate (or sulfate waste) is defined as sulfate-containing materials arising as by-products from industrial processing or environmental control. For example, the wet process method for phosphoric acid manufacture involves reacting phosphate rock with sulfuric acid. The by-product of the reaction is an impure calcium sulfate called phosphogypsum. The phosphogypsum contains 30 to 40% sulfate together with 1% P_2O_5 residual. The P_2O_5 residual alters its properties sufficiently to make it noncompetitive with natural gypsum for practically all applications.

At the other extreme of waste sulfate compositions are solid products which are generated by lime (or limestone) neutralization of spent pickle liquors or acid mine drainage. In these cases, the neutralization is done to destroy acid which means that most of the solids are hydrated iron oxides. Some calcium sulfate is occluded with the oxides ranging from 3 to 16% sulfate by weight.

Between these two extremes are waste sulfates generated by flue gas desulfurization processes using lime or limestone scrubbing. Sulfate contents of flue gas desulfurization solids range from 2 to 15%, because the materials are diluted with unreacted limestone and, in some cases, with fly ash which is scrubbed out along with the sulfur oxides. Thus, flue gas desulfurization wastes can be quite variable with respect to sulfate content depending upon particular SO_x scrubbing practices.

The concern with sulfate waste lies in the vast amounts of materials being produced. We have estimated the annual rate of phosphogypsum generation to be approximately 30 million tons. Flue gas desulfurization currently produces about 1 million tons per year based on sulfur content

of coal burned. If one includes the unreacted scrubbing agents and fly fly ash in these values, a more realistic estimate would be nearer 2 million tons per year. In addition, as more and more scrubbers come on line, the rate of flue gas desulfurization solids production will increase drastically. The Environmental Protection Agency estimates that flue gas desulfurization waste generation could be 100 million tons by 1980 to 1988. A good estimate for waste sulfate produced by pickle liquor and acid mine drainage neutralization could not be made. However, an educated guess at the production rate of these materials is on the order of 1 million tons per year.

At the present time, most of these sulfate wastes are accumulating in piles. Adequate disposal of the piles represents a real and growing problem. In order to determine how they might be used constructively (or disposed of) in road building activities, six sulfate wastes were mixed with 31 soils representing a broad spectrum of textural and mineralogical properties. Soils were chosen on the basis of their proximity to sources of the sulfate waste. These choices resulted in the matching of one or more sulfate wastes to each soil. The matching of six sulfate wastes with 31 soils yielded 56 soil/sulfate waste combinations for laboratory study.

The laboratory study involved determining Atterberg Limit and moisture/density relationships for the 56 soil/sulfate waste combinations. In addition, unconfined compressive strengths were determined in most soil/sulfate waste and soil/sulfate waste/lime systems. Selected systems were chosen to determine effects of sulfate waste/lime/fly ash, sulfate waste/portland cement, and sulfate waste/cement kiln dust combinations on unconfined compressive strength. In addition, a few systems were chosen for observing freeze-thaw characteristics and volume stability with respect to shrink-swell potential.

Raw data generated from the experiments have been analyzed using linear multiple regression techniques. In particular, the unconfined compressive strengths have been evaluated with respect to moisture content, curing time, and level of sulfate waste (and lime) addition. This analysis has provided a series of linear regression coefficients, plus their standard deviations and statistical significances for all of the soil/sulfate waste systems studied during the program. Comparison of the regression coefficients with one another has permitted the development of general principles for using sulfate waste for remedial treatment of soils.

The report has been prepared in two volumes. Volume I--Discussion of Results--contains the details of experimental work together with the interpretation of the data. Conclusions and Recommendations are presented at the end of the Volume I text as Sections V and VI. The raw data have been reduced into graphical and tabular form to facilitate the discussion. The figures and tables referenced in the text can be found at the end of Volume I.

Volume II--Appendixes--contains a description of literature reviewed during the program as Appendix A; the Atterberg Limits and moisture-density relationships in Appendix B; the unconfined compressive strength data obtained from the specimen crushing as Appendix C; and an outline of the multiple regression analysis procedure plus a sample calculation in Appendix D.

II. CHARACTERIZATION OF SOILS AND SULFATE WASTES

In order to meet the objectives of the program, we undertook the matching of soils and sulfate wastes on the basis of geographical location of sulfate wastes. Source locations of sulfate waste of various types were identified, and soil series within a 100-mile radius of the source were deemed to be candidate soils for evaluation in the experimental study. The list of source areas was submitted to the Soil Survey Interpretation Division, Soil Conservation Service, U.S. Department of Agriculture, along with the request that soils in the vicinity of the areas having AASHTO classifications of A-4 through A-7 in the lower horizons be identified. Following the identification of candidate soils, we were able to select 31 soil series for use in the experimental program.

Six sulfate wastes were donated by various industries for evaluation. We used three phosphogypsum by-products of the manufacture of phosphoric acid by the wet process; two flue gas desulfurization solids from power plants equipped with lime/limestone based SO_x scrubbers; and one neutralized acid mine sludge. The acid mine drainage material is chemically similar to solids generated by pickle liquor neutralization products for the steel industry, and has been considered a substitute for the neutralized pickle liquor waste in the study. The six sulfate wastes used for the study have been characterized with respect to their chemical composition which is discussed later.

Following acquisition of the sulfate wastes and soils, we proceeded to evaluate the effects of sulfate waste addition on Atterberg Limits and moisture/density relationships of the soils. The studies concerning Atterberg Limits and moisture/density permitted the classification of soil responses to sulfate waste addition on the basis of plasticity index a feature which greatly facilitated interpretation of experimental data.

The main thrust of the program, however, was directed towards unconfined compressive strengths of soil/sulfate waste and soil/sulfate waste lime mixtures. In addition, a few systems were evaluated with respect to unconfined compressive strength of soil/sulfate waste/lime/fly ash systems, soil/sulfate waste/cement systems, and soil/sulfate waste/kiln dust systems. The evaluation of the unconfined compressive strength effects is reported in detail in Sections III and IV of this report.

Finally, the experimental data were analyzed using linear multiple regression techniques to establish the basis for data interpretation.

This approach has allowed us to estimate the degree to which sulfate waste (and other additives) affects unconfined compressive strength of soils, by the magnitude and algebraic sign of various independent parameters affecting unconfined compressive strength. In addition, we could establish the standard deviations for the regression coefficients, which in turn establish the statistical significance (level of confidence) for the regression coefficient.

In this section, we shall discuss the following features of the program methodology:

* Soil/sulfate waste matching.
* Sulfate waste characterization.
* Atterberg Limits and moisture/density of soil/sulfate waste systems.
* Data analysis procedures.

A. Establishment of Soil/Sulfate Waste Systems

The first task involved with choosing soils to be evaluated with sulfate waste was to locate sources of sulfate waste. The identification of sulfate waste sources revealed that two materials constituted the bulk of the sulfate waste problem--phosphogypsum from the fertilizer industry, and flue gas desulfurization solids generated at power plants having lime/limestone based SO_x scrubbers. These materials are found at specific locations and are easily identifiable. Other sources of sulfate waste such as neutralized pickle liquor solids from the steel industry and acid mine drainage wastes are much more widely dispersed and do not appear to be available in the same quantity as are phosphogypsum and flue gas desulfurization solids.

The largest source of sulfate waste by far is phosphogypsum. Wet process phosphoric acid production plants are estimated to generate approximately 40 to 45 million tons per year of phosphogypsum, most of which is located in Florida and around the Gulf Coast. Flue gas desulfurization solids, on the other hand, are being generated at a rate of 1.5 to 2 million tons per year at the present time. The largest single source of the flue gas cleaning waste is the Kansas City Power and Light/Kansas Gas and Electric plant at LaCygne, Kansas, which produces nearly 1 million tons per year of the material.

The specific sources of phosphogypsum and flue gas desulfurization solids have been ranked according to size of sulfate waste generation. The source locations are mapped in Figure 1, and sulfate waste generation for each area is ranked in Table 1. The largest source is found near the Florida phosphate fields where the estimated annual production rate of phosphogypsum is 24 million tons. Thus, excluding central Florida, there are 15 to 20 million tons of phosphogypsum available at a dozen locations in the country.

The values for flue gas desulfurization solids shown in Table 1 are based upon 1974 data. The amounts (and locations) will increase substantially over the next few years as more SO_x controls come on-line at coal-fired electric power generating facilities. It is estimated that when these new facilities become operational the quantity of flue gas desulfurization solids will increase by 8 to 10 million tons per year.

The locations identified in Figure 1 were used as the basis for identifying soils used in the experimental study. The source areas 1 to 14 were submitted to the Soil Survey Interpretation Division of the Soil Conservation Service (SCS), U.S. Department of Agriculture. We did not include soils in the Western United States, because of the much larger quantities of sulfate in the east and midwest. The SCS then had the principal Soil Correlator in their regional office compile a list of soils in the vicinity of the source area. The three regional SCS offices making this compilation were: the Eastern Division, Upper Darby, Pennsylvania; Midwest Division, Lincoln, Nebraska; and Southern Division, Forth Worth, Texas.

In addition to location, the SCS was asked to use AASHTO classification for soil series at depths of 10 to 30 in. as another criteria for selection. The subsoils were to be classified A-4, A-6, or A-7 in order to be suitable for the program. We chose the 10 to 30 in. range, since soil stabilization for highway purposes normally involves shallow subsoil rather than topsoil.

The regional SCS offices compiled a total of 91 soils series which met the criteria of location and AASHTO classification which were used as the basis for soil selection. The Soil Series Interpretation Surveys of each of 91 soils contained the detailed description of each soil series. Upon examination of the descriptive information, it was decided that the soil family description was an appropriate basis for making final selection of soils for study. The 91 soil series identified by the SCS regional offices are grouped according to family description

in Table 2, along with their source area locations. The underlined soils are the ones chosen for laboratory work, and their approximate locations are mapped in Figure 2. Where possible, the choice of a soil within a particular family classification was based on the number of other soils of different classification in the same area. This selection criteria allowed us to collect several soils of the same type with a minimum of travel.

The soil family description is a measure of soil texture, mineralogy, and thermal regime. As will be discussed later, (Section IV-C) soil texture was a key criterion for classifying the soils gathered for laboratory evaluation. The SCS has designated the family textured description on the following basis:[1/]

Loamy - less than 35% clay (0.002 mm diameter), but more than 15% coarser than very fine sand (0.1 mm diameter).

Coarse-Loamy - less than 18% clay, but more than 15% coarser than very fine sand.

Fine-Loamy - clay content between 18 and 35%, more than 15% coarser than very fine sand.

Silty - less than 35% clay, and less than 15% coarser than very fine sand.

Coarse-Silty - less than 18% clay, and less than 15% coarser than very fine sand.

Fine-Silty - clay content between 18 and 35%, less than 15% coarser than very fine sand.

Clayey - more than 35% clay.

Fine - clay content between 35 and 60%.

Very fine - clay content greater than 60%.

1/ Soil Survey Staff, Soil Conservation Service, U.S. Department of Agriculture, "Supplement to Soil Classification System (7th Approximation)," Washington, D.C., 1967, p. 38.

After soils were selected, contact was made with local SCS soil scientists or area conservationists. These persons made arrangements for our sampling team to collect the soils. Soil acquisition at the type location (the site at which descriptive information for the SCS Soil Survey Interpretation is taken) was done wherever possible. However, in some cases alternate sites were used. The county and state in which the type location is found for each of the 31 soil series chosen is cited in Table 3. The county/state in which the soil sample was actually collected is also given.

Approximately 200 lb of soil was collected for each of the 31 soil series chosen for study. These soils were collected in the B horizon at depths of 10 to 30 in. Following collection, the soil was shipped to the Midwest Research Institute laboratories in Kansas City to be used for evaluation with respect to sulfate waste addition.

B. Sulfate Waste Characterization

Sulfate waste from several of the source areas (identified with an asterisk in Table 1) was donated for the experimental study. Six samples of sulfate waste were used: three samples of phosphogypsum, two flue gas desulfurization solids, and one neutralized acid mine drainage solid. As stated earlier, the acid mine drainage material is similar to that obtained by lime/limestone neutralization of spent pickle liquor. The six samples are:

* PG1--Phosphogypsum (Florida). Farmland Industries, Inc., supplied a phosphogypsum sample from their Green Bay, Florida, plant.

* PG2--Phosphogypsum (North Carolina). Texas Gulf, Inc., shipped us phosphogypsum from their Aurora, North Carolina, facility.

* PG3--Phosphogypsum (Texas). Olin Corporation donated phosphogypsum waste generated at their Pasadena, Texas, plant.

* FG1--Flue Gas Desulfurization Solids (Illinois). Commonwealth Edison Company sent us waste sulfate (mixed with fly ash) from their Will County, Illinois, No. 1 flue gas desulfurization unit.

* PG2--Flue Gas Desulfurization Solids (Kansas). Kansas City Power and Light Company permitted us to collect a sample of sulfate waste sludge from the settling pond at their LaCygne, Kansas, power generating facility.

* AMD--Neutralized Acid Mine Drainage Solids (Pennsylvania). Commonwealth of Pennsylvania, Department of Environmental Resources suggested that we use neutralized acid mine drainage from sludge beds at their Hollywood, Pennsylvania, mine drainage treatment facility.

The six sulfate wastes were analyzed for a number of constituents to establish compositional characteristics of the three sulfate waste types. The results of the various analyses are summarized in Table 4. The compositions shown are based on oven-dried materials. Sulfate wastes, being generated from aqueous systems, normally contain large amounts of free water, and the amounts of water contained in them are highly variable. At the bottom of Table 4, moisture contents of as-received sulfate waste and of air-dried materials are given. As-received materials are quite wet compared to air-dried materials except for the North Carolina phosphogypsum.

The free water content of sulfate waste is an important factor in their utilization as soil stabilization agents. The moisture content of the materials must be taken into account as contributing to overall moisture in the treated-soil system. On the other hand, the effects of sulfate waste on soil properties depend largely on the chemical composition of the waste itself. Thus, the amount of sulfate waste to be used should be based upon an oven-dried solids basis, while the moisture content, established by oven-drying, can be used to estimate ultimate moisture contents of the total system.

Examination of the oven-dry chemical compositions of the sulfate wastes reveal substantial differences among the materials. The most significant differences lie in the sulfate content. The three phosphogypsums contain very much more sulfate (33 to 42%) than do the flue gas desulfurization and acid mine drainage materials (1 to 13%). On the other hand, the calcium contents of all six materials do not differ widely. The combination of sulfate and calcium for the sulfate wastes indicate that calcium sulfate is a principal constituent in phosphogypsum; while calcium sulfate is mixed with other calcium-containing materials in the flue gas desulfurization and mine drainage sludges.

The wastes have been further characterized by X-ray powder patterns and the results for the sulfate wastes are presented in Figure 3, together with those reported for gypsum and calcium carbonate (calcite). The phosphogypsum waste patterns are nearly identical to the gypsum standard, as would be expected from the chemical analysis. The absence of spacings not associated with gypsum in these samples suggest that the phosphogypsums are not contaminated by other crystalline substances.

The X-ray spacings of the flue gas desulfurization and neutralized acid mine drainage materials are much more complex than those of the phosphogypsums. However, certain ones of the observed spacings correspond very well to those reported for calcite ($CaCO_3$), indicating that a major constituent in these materials is unreacted limestone. Spacings which are not due to calcite suggest that the flue gas desulfurization wastes contain other crystalline materials. These materials are probably associated with the fly ash components in the wastes. On the other hand, the acid mine drainage-derived waste appears to be primarily calcium carbonate.

The silica, iron oxide, and alumina contents of the wastes also differentiate the chemical natures of the sulfate waste. The sum of these three constituents are 18.6%, 12.3%, and 14.3% for PG1, PG2, and PG3, while they are 31.3% in FG1, 21.1 to 74.8% in FG2, and 40.6% in AMD. The phosphogypsums are clearly less contaminated with soil-related oxides (silica, iron oxide, and alumina) than are the low-sulfate-containing materials. The soil-related oxides have an effect on the response of soils to the addition of sulfate waste, as will be pointed out in later discussion.

The two sets of values shown in Table 4 for the Kansas flue gas desulfurization solids (FG2) represent the values for sieved and unsieved materials. The operation of the flue gas scrubbing unit at LaCygne, Kansas, results in a sludge which contains both sulfate waste and ash. The sulfate waste sample was collected near the outlet of the scrubber discharge to the pond where dense materials in the scrubbed solids will settle first. A large part of the dense material was a coarse ash, which was separated by sieving through a 40-mesh screen. The -40 material was used as the FG2 sulfate waste in the experimental program. As can be seen from the compositions in Table 4, the bulk of the +40 material contained silica, iron oxide, and alumina. In the -40 material, sulfate content was increased to 2.7% from 0.7%, calcium from 13.9% to 41.2%, and loss on ignition from 5.8% to 32.2%, The sulfate, calcium, and loss on ignition suggest that a principal component of the FG2 sample was unreacted limestone which settles shortly after discharge into the pond.

The relative proportions of silica, iron oxide, and alumina are roughly the same in FG1 and FG2, while differing substantially from that in AMD. The acid mine drainage-derived material has much more iron

oxide and alumina compared to the flue gas desulfurization solids. This fact arises because soluble iron and aluminum sulfates are a major component of acid mine drainage and are precipitated during neutralization. In the flue gas desulfurization-derived wastes, iron and alumina contents are associated with ash content rather than soluble salts. Thus, this distinction tends to affect response of soils to addition of the low sulfate-content waste.

The amount of alumina in the neutralized acid mine drainage sludge is higher than that which would be expected in neutralized pickle liquor from steel manufacturing facilities. Solids obtained from lime/limestone neutralized pickle liquor would be high in iron oxide like the AMD sample. Since alumina is lacking in pickle liquor-derived sulfate wastes, they are expected to be less responsive to altering soil properties than the effects noted with AMD, particularly with respect to their combinations with lime. As will be seen, the AMD waste was the least responsive of the sulfate wastes towards strength development when mixed with soils. This lack of response is believed due to the high iron oxide content of the neutralized acid mine drainage solids.

The six sulfate waste samples were all analyzed for sulfite, even though sulfite was expected only in the flue gas desulfurization solids. The sulfite contents of FG1 and sieved-FG2 are greater than those of the other wastes, but still amount to only 0.1 to 0.2% of the total composition. Thus, it appears that aging of the flue gas desulfurization wastes tends to convert sulfite to sulfate. Effects on soil properties are probably influenced more by total sulfur content than by sulfite/sulfate ratios.

All samples were also analyzed for phosphate and fluoride, since phosphogypsum contain traces of these materials. As expected, the phosphogypsum contains more phosphorus and fluoride than do the other sulfate wastes. These constituents do not appear to have a significant effect on soil properties. The fluoride content of the phosphogypsums is fixed by the siliceous materials in the wastes.

The loss on ignition values reported in Table 4 represent three different phenomena for the various sulfate waste types. The values for the three phosphogypsums are associated with the dehydration of the gypsum components. Each mole of the gypsum contains 2 moles of water which will be lost when the material is heated above about 180°C (ca. 350°F). The loss on ignition reflects the loss of these waters

of crystallization. On the other hand, loss on ignition values for the two flue gas desulfurization wastes represents the loss of carbon dioxide by the unreacted limestone constituents. When calcium carbonate is heated to the 900 to 1000°C (1652 to 1832°F) range, carbon dioxide is liberated and is reflected in a loss of weight. Fianlly, most of the loss on ignition for the acid mine drainage-derived waste is associated with the dehydration of iron and aluminum hydroxides precipitated in the neutralization. These hydroxides are amorphous and lose water over a wide temperature range (about 200 to 600°C, 392 to 1112°F).

The last parameter presented in Table 4 is pH, obtained from sulfate waste/water slurries. The phosphogypsums are clearly more acidic than are the flue gas desulfurization or acid mine drainage wastes. The higher acidities of phosphogypsum are associated with the manufacture of phosphoric acid. This process involves reacting phosphate rock with sulfuric acid to extract the phosphate value. Following reaction, the aqueous phase containing phosphate is separated from the phosphogypsum by-product. In order for this separation to be complete, an acidic pH is required. On the other hand, flue gas desulfurization and acid mine drainage treatment are basically neutralization processes. Thus, one attempts to maintain pH close to neutrality to ensure complete reaction. This process control is thus reflected in the pH's of the resulting by-products.

The preceding detailed discussion of sulfate waste characteristics has been presented to show the differences among the various types of sulfate waste which are candidate agents for remedial treatment of soils. The effect of these wastes on the Atterberg Limits and moisture/density relationships of the 31 soils chosen for evaluation is presented next.

C. Atterberg Limit and Moisture/Density Relationships of Soil/Sulfate Waste Systems

1. Soil/sulfate waste system characterization - The 31 soils and 56 soil/sulfate waste combinations selected for evaluation by rationale discussed in Section II-A were evaluated with respect to Atterberg Limits and moisture/density relationships. Results of this evaluation are presented in Appendix B in Volume II of this report. Atterberg Limits were obtained using standard procedures. Liquid limit was determined using

methods described in AASHTO specification T-89, and plastic limit as specified in AASHTO T-90. The moisture/density relationships were established using a Harvard Compaction Apparatus as described by Wilson.[1/]

Upon acquisition of the Atterberg Limit data, it became apparent that interpretation of laboratory results could be greatly facilitated by ordering the various soils into four arbitrary classifications based on plasticity index and mineralogy:

* Class I Soils: Plasticity Index NP (nonplastic)-10;

* Class II Soils: Plasticity Index 10 to 25;

* Class III Soils: Plasticity Index > 25, Nonmontmorillonitic; and

* Class IV Soils: Plasticity Index > 20, Montmorillonitic.

The classifications of the 31 soils togetner with their physical property tests are shown in Table 5. For purposes of discussion, the Class I soils are considered coarse-grained, Class II soils as medium-grained, and the Classes III and IV soils as fine-grained. Distinction between Classes III and IV is based on mineralogical differences. One of the montmorillonitic Class IV soils--Fellowship--is more coarse-grained than other montmorillonitic soils, which is reflected in its plasticity index of 20 to 25.

A linear regression analysis of the Atterberg Limit and moisture/density data was undertaken to relate the effects of sulfate waste addition on soil properties. The methodology of the regression procedure is described in Section II-D of this report. The procedure permits the development of linear equations relating liquid limit, plasticity index, optimum moisture, and maximum density of the several soils to sulfate waste addition. In addition, the standard deviations of the sulfate waste coefficient in the various equations have been established, as well as the statistical significance of the effects of sulfate waste addition. A discussion concerning the effects of sulfate waste addition on the Atterberg Limits and moisture/density relationships of the soils follows.

1/ Wilson, S. D., "Suggested Method of Test for Moisture Density Relations of Soils using Harvard Compaction Apparatus," in ASTM Committee D18 on Soils and Roads for Engineering Purposes, Procedures for Testing Soils, 4th ed., American Society for Testing and Materials, PhilaDelphia, Pennsylvania, December 1964, pp. 160-162.

2. Atterberg Limits - The linear equations for liquid limit as a function of sulfate waste addition are presented in Table 6, and those for plasticity index in Table 7. The effects of sulfate waste addition on Atterberg Limits of Classes I and II soils were consistent in all cases, with only the magnitudes differing. The liquid limit was found to increase with increasing sulfate waste application as reflected in the positive sign of the coefficient of the independent variable (percent sulfate waste) in the linear regression equation. The plasticity index tended to decrease with additional sulfate waste. These observations indicate that the plastic limit increases at a faster rate than does the liquid limit when sulfate waste is mixed with soils. The increase in the moisture required to reach a plastic state is desirable in subgrade material, since the soil is less likely to deform than that of untreated soil at the same moisture content.

The most significant quantitative changes in the Atterberg Limits of Classes I and II soils associated with FG1 and AMD addition. These two wastes, although very different in texture and appearance, are similar in that they possess two factors that could have a bearing on the effect their addition has on plastic limits. Both wastes are low in sulfate content, because of inorganic impurities, such as fly ash and iron oxide, and they contain appreciable quantities of unreacted limestone (calcite). The predominant factor could be the tendency of inorganic materials to sorb water, which then would require a higher moisture content to obtain a moisture film between soil particles thick enough to reach the plastic limit. The attractive forces between soil particles at the liquid limit are much weaker than at the plastic limit, because of the greater amount of water in the mixture. Therefore, the effect of FG1 and AMD, so prominent at the plastic limit, plays a lesser role at the liquid limit where overall moisture requirements are not greatly affected by the sulfate waste addition.

The fine-grained, Class III and IV soils also show a decrease in plasticity index but exhibit a mixed effect on the liquid limit. For all the soil/waste systems the significance levels are lower for the fine-grained than for the coarse-grained soils. In general, the liquid limit is decreased by sulfate waste addition except with FG1 and AMD. An exception is noted with the Class III nonmontmorillonitic soils where the liquid limit increases with FG1 and AMD addition. A close examination of the Class IV data show that while the liquid limit is decreasing, the significance of the regression is much less for FG1 and AMD addition as compared with the other wastes. This observation suggests that higher amounts of unreacted limestone in the wastes counteract the tendency of high sulfate content wastes to decrease the liquid limit. The plasticity index for the fine-grained soils decreases with the exceptions of FG1 with Class IV soils and AMD with Class III soils.

The particle size of the sulfate waste may also have a bearing on the liquid limits. For the coarser-grained, Classes I and II soils, sulfate waste particles are smaller than those of the soils. Hence, more water can be held by the fine-grained sulfate waste particles before a liquid state is reached. On the other hand, sulfate waste particles are more nearly the same size or larger than the soil particles in Classes III and IV soil systems. When water is added to mixtures of sulfate wastes with these soils, cohesion of soil particles is not as great and liquid limit decreases. When the waste has a high sulfate content, the tendency for the interdiction of cohesive forces of the soil is greater than that for low sulfate content wastes where soil-like impurities are present, e.g., fly ash in the FG1 and FG2 systems and iron/aluminum oxides in the AMD systems.

2. Moisture/density relationships - Optimum moisture and maximum density of soil/sulfate waste systems have been determined. The linear equations relating optimum moisture to sulfate waste content are presented in Table 8 and those for maximum density in Table 9.

The effect of sulfate waste addition on moisture/density relationships is very uniform for all Class I and II soils evaluated. The optimum moisture is found to increase with increasing sulfate waste content, while the maximum dry density decreases with waste addition. The decrease in density is due to the displacement of soil by material of lower specific gravity, e.g., calcium sulfate, calcium carbonate, etc., that constitutes the sulfate waste and by the affinity of sulfate waste moisture.

This tendency may also be related to relative size between sulfate waste and soil. In coarse-grained soils, sulfate waste and moisture tend to fill voids in the structure. Sulfate waste tends to hold more moisture than the unadulterated coarse-grained soils; therefore, optimum moisture content increases. Since sulfate waste/moisture is less dense than soil particles themselves, and since the sulfate waste/moisture material acts as fine-grained filler in a coarse-grained system, fewer soil grains can be compacted into a given volume. Therefore, one would expect the maximum density decrease observed when sulfate waste is added to coarse-grained soils at optimum moisture content.

In the case of the finer-grained soils (Classes III and IV), the effect of sulfate waste on maximum density and optimum moisture is quite variable. In general, the magnitudes of the sulfate waste coefficient are smaller than those associated with the Classes I and II systems. However, no clear-cut trends towards either increase or decrease is noted, nor do the stastical significances indicate strong relationship between the variables. These weaker relationships may be due to the more uniform particle size distribution in the mixture. Uniformity

of particle size with the mixture makes mixing of soil and sulfate waste more critical. If the mixtures are not thoroughly homogeneous, the compaction of the mixtures should vary, resulting in a fairly broad distribution of observed data. We believe this to be the case when maximum density and optimum moisture are determined for fine-grained soil/sulfate waste mixtures.

D. Data Analysis Procedure

All data generated by the various tests during the program have been analyzed using linear multiple regression. The method used for the regression analysis has been outlined in a step-by-step procedure by Kramer.[1/] Basically, this procedure consists of summing the various independent variables and one dependent variable, along with their squares and cross-products. These sums are manipulated by standard analysis of variance procedures to obtain the total sum of square differences for each of the squares and cross-terms considered. The values are then entered into a matrix, and the matrix solved. Solution of the matrix results in a set of regression coefficients which relate the effects of the several independent variables on the one independent variable.

The calculated intermediate values involved in determining the regression coefficients are then used to create an inverted matrix from which standard deviation for each regression coefficient can be established. The matrix inversion procedure again requires a systematic manipulation of the numbers.

Throughout the solution of both the original matrix for regression coefficients and the inverted matrix for standard deviations, simple checks are provided at each step of the procedure to prevent arithmetic mistakes. If checks do not balance properly, then one needs only to return to the calculation immediately preceding the check point to find the mistake. With a little experience with the computation system, it is possible to relate five independent variables to one dependent variable in about 45 min to 1 hr time using an electronic calculator.

1/ Kramer, C. Y., "Simplified Computations for Multiple Regression," in the CRC Handbook of Tables for Probability and Statistics, 2nd Edition, Chemical Rubber Company, Cleveland, Ohio, pp. 41-46 (1968).

Following computation of the regression coefficients and standard deviations, the statistical significance of the coefficient can be determined using the "Student-t" test. The ratio of the regression coefficient to its standard deviation gives the statistical "Student-t" factor. Using the standard tables of "Student-t" together with the number of individual datum included in the analysis, it is an easy matter to ascertain the statistical significance (degree of confidence) of the regression coefficient.

For the study at hand, the most used independent parameter was unconfined compressive strength. Unconfined compressive strength data of soil specimens are determined by three independent parameters: moisture content, curing time, and level of treatment agent. Moisture and time were used throughout the analysis in every case. Level of treatment was broken down into specific components so that the effect of a specific component on the system could be established. A sample calculation for one soil/sulfate waste/lime system (Exum/PG2/lime) is presented as Appendix D in Volume II of this report.

The individual components of treatment included in the study were sulfate waste, lime, fly ash, portland cement, cement kiln dust. When these components were mixed with one another, each combination resulted in two or three independent variables. Thus, in lime/sulfate waste-treated systems, unconfined compressive strength results are correlated by four independent variables--moisture, time, lime content, and sulfate waste content; whereas in lime/sulfate waste/fly ash-treated systems, five independent variables are required--moisture, time, lime content, sulfate waste content, and fly ash content.

The regression coefficients indicate the degree of influence of each independent variable on unconfined compressive strength. The units of the coefficient were psi per percent unit for those associated with moisture and the various additives, and psi per day for the time coefficient. By using the relative magnitudes of the coefficients as a guide, it is possible, for example, to estimate how a 1% change in the amount of additive used will affect unconfined compressive strength, or how a day's curing will affect the strength.

The relationship between unconfined compressive strength and the various independent variables has been assumed to be linear. This assumption probably does not represent the "best fit" of the data, especially with respect to the time parameter. It was chosen because it is the simplest format to use with the data, and has proved to be adequate for determining first-order effects of treatment conditions on unconfined compressive strength of soils.

In addition to unconfined compressive strengths, Atterberg Limit data and moisture/density relationships have been used as independent variables using the above methods. In these cases, however, only one independent variable--sulfate waste content--was considered. Thus, it has been possible to develop equations relating the effect of sulfate waste on the following soil properties: liquid limit, plasticity index, maximum density, and optimum moisture.

In subsequent sections of this report, the results of the test analyses will be the basis of discussion. The analyses of Atterberg Limit and moisture/density data have been discussed in Section II-C, and the general results of unconfined compressive strength data analyses are discussed in Section III. The details of specific effects caused by treatment of specific soils are presented in Section IV.

III. EFFECT OF SULFATE WASTE ADDITION ON UNCONFINED COMPRESSIVE STRENGTH OF SOILS

This section will discuss unconfined compressive strength development of soil/sulfate waste systems, and how these strengths are affected by additions of other materials. The raw experimental data from which the analyses have been conducted are presented in Appendix C (Volume II) of this report.

Soil/sulfate waste specimens were molded using the Harvard Compaction Apparatus at optimum moisture content as described in Section II-C. As we progressed into soil/sulfate waste/lime systems, we found that optimum moisture content was often insufficient to produce proper consistency for compaction. In these cases, more water was added to obtain better mixture consistency. Following preparation, the specimens were wrapped with Saran wrap to prevent moisture egress or ingress and stored in a cabinet maintained at 72°F and 100% humidity. Specimens were sacrificed to obtain undonfined compressive strength after 1, 7, 14, and 28-day cure. The testing was conducted using a Instron Universal Testing Instrument (Model TT-CM-M1) at a loading rate of 0.1 cm/min.

Upon acquisition of the unconfined compressive strength data, multiple linear regression analysis of each soil sulfate waste system was conducted. Results of the data analyses are the basis for the subsequent discussion in this section.

The overall format of the discussion here is designed to show the general effects on unconfined compressive strengths of soils treated with sulfate waste, and with sulfate waste plus other additives, i.e., lime, fly ash, portland cement, and cement kiln dust. In addition to the general unconfined compressive strength studies, selected soil/sulfate waste systems have been evaluated with respect to freeze-thaw durability and volume stability. These results are included as part of the following discussion. Discussion of the effects of the various treatments on specific soils is presented in Section IV on a soil-by-soil basis. The sequence of the discussion is as follows:

* Untreated soils
* Sulfate waste-treated soils
* Lime-treated soils
* Lime/sulfate waste-treated soils
* Lime/sulfate waste/fly ash-treated soils

* Cement/sulfate waste-treated soils

* Kiln dust/sulfate waste-treated soils

* Durability/stability studies

A. Untreated Soils

The unconfined compressive strength data for untreated soils (control samples) have been analyzed using linear regression techniques. This analysis indicates the relative importance of two parameters affecting strength--moisture content and curing time. Linear regression coefficients, standard deviations, and statistical significance for moisture and time are shown in Table 10.

The data analysis results in Table 10 indicate that neither moisture nor time have any great effect on the unconfined compressive strength of untreated soils. In cases where the coefficient is large, e.g., moisture coefficient for the Atkins series, the standard deviation is also large which makes the value nonsignificant in the statistical sense. However, the results do indicate trends, particularly with respect to moisture.

Disregarding the statistical significance of the moisture regression coefficient, the results indicate that increasing water content will yield a decrease in unconfined compressive strength, i.e., the moisture coefficient is generally negative. These results mean that increasing moisture content in a soil will tend to decrease strength, a result that would be expected. On the other hand, decreased moisture implies higher strength. Since the specimens were all fabricated near the optimum moisture content, the results imply that most of the soils studied would yield higher compressive strengths if worked slightly below the optimum moisture content.

The magnitude of the time coefficients clearly indicates that 1 day's curing time has less effect on unconfined compressive strength than does a 1% change in moisture content. These results suggest that once soils are compacted, they undergo little internal change with time which affects strength, another result which is expected.

Many of these coefficients which are indicated as being statistically significant in Table 10 have been derived from very few samples. Thus, there is some question whether this significance is real or accidental. For example, the data for the Norfolk series are based on data from only five specimens. The 95% significance level for

these soils seems a bit unusual for such a small sampling, and may reflect accidents of value numerical rounding rather than absolute trends. The effect of rounding is definitely observed in the zero moisture coefficients for some soils, i.e., Convent, Delray, Kendrick, and Commerce. The absolute nondependence of moisture on strength as indicated by these coefficients is much too rigid an interpretation and arises solely because of the nearly identical moisture contents in the small number of samples tested.

B. Sulfate Waste-Treated Soils

The soils were mixed with selected sulfate wastes to determine the effect of sulfate waste additive on their unconfined compressive strengths. The unconfined compressive strength data for these systems were analyzed by linear regression methods to determine coefficients, standard deviations, and statistical significance for three parameters: moisture content, curing time, and sulfate waste treatment level. The strength data for the control samples (zero sulfate waste level) were also included in the data analysis. Results of the data analysis are tabulated in Table 11. Because of the longer sampling base, a greater degree of confidence can be placed on the statistical significance for the soil/sulfate waste systems.

Sulfate waste additive has a significant effect on 6 of the 14 Class I systems. Phosphogypsum, a high sulfate content waste, has a positive effect on most of the soils tested, although the effects are not always statistically significant this pattern is observed also for the low sulfate content wastes, flue gas desulfurization and acid mine drainage neutralization solids. However, the beneficial effects of sulfate waste additive tend to be offset by the negative effects of moisture. Six of the 14 Class I soil/sulfate systems have negative moisture regression coefficients which are significant at the 90% level or higher. Thus, in order for sulfate waste additives to have a positive effect on strength formation, the soil sulfate waste mixtures should be compacted at less than optimum moisture content for optimum strengths.

Time has relatively little effect on strength development of soil/sulfate waste mixtures involving the Class I soils. The time dependence is small (about the same order of magnitude observed with the control samples) and is significant in only 2 of the 14 systems. Definite trends pointing towards either positive or negative effects of time on strength development do not exist for the Class I soil/sulfate waste systems, indicating that sulfate waste serves as inert fines.

As one moves to the more fine-grained soils in Class II, the data indicate that sulfate waste additive can affect strength either positively or negatively. For the phosphogypsum systems, strengths tend to be diminished by sulfate waste additives. On the other hand, five of the nine low sulfate waste systems in Class II indicate increased strength with sulfate waste additive, and the remaining four tend to have decreased strengths. Thus, it appears that with the low sulfate content wastes, the particular soil/sulfate waste interactions become important in determining whether sulfate waste enhances or degrades unconfined compressive strength. These interactions can only be established by testing the soil/sulfate waste mixtures.

Moisture tends to have a negative effect on the Class II soil/sulfate waste systems, and the effect is more pronounced in the low-sulfate content (FG1, FG2, and AMD) systems. The magnitude of the negative moisture effect in these latter systems appears to be much greater than observed in the Class I systems. Likewise curing time tends to have a degrading effect on many of the Class II soil/sulfate waste systems involving FG1, FG2, and AMD. This trend is less pronounced in the phosphogypsum systems.

In the fine-grained Classes III and IV systems, sulfate waste and moisture both appear to degrade strengths. The influence of curing time follows closely the trends established in the Class II systems, i.e., strengths deteriorate slightly with time. However, the number of occasions that time is statistically significant is much less than that associated with either moisture or sulfate waste content.

In summary, the addition of sulfate waste to soils tends to have a positive effect on the strengths of coarse-grained soils and a negative effect on fine-grained soils. However, the magnitude of the effects is not large, so that the overall consequence of adding sulfate waste to soil is fairly small with respect to strength. In general, a high moisture content is deleterious towards strength. Thus, if one incorporates sulfate waste with soil, a moisture content a little less than optimum should be considered.

Because of the minimal effects of sulfate waste additives on soil strengths, sulfate waste can be added to soils as a means of disposal, but not as a means of improving strength. As will be seen in subsequent discussions, strengths of soil/sulfate waste mixtures are much less than those achieved by conventional lime or portland cement treatment. If sulfate waste by itself is used as a treatment agent, it would most likely be used in conjunction with the coarse-grained soils. In the medium-grained soils, classified here as Class II soils, one would probably consider a low-sulfate content waste, e.g., flue gas desulfurization or treated acid mine drainage solids, rather than a high-sulfate content waste like phosphogypsum. Because of the tendency for sulfate

waste to degrade soil strengths in the fine-grained soils, one would probably not consider sulfate waste treatment in these cases.

C. Lime-Treated Soils

The effect of sulfate waste treatment on unconfined compressive strength of soils is minimal, an observation which confirmed expectations. However, treatment with sulfate waste and lime in combination would be expected to improve strength properties of soils. As will be seen later, this improvement was confirmed. In order to measure the degree of improvement in soil strengths created by sulfate waste/lime treatment, one must first know what are the effects of lime treatment alone. These effects, as determined by linear regression analysis of unconfined compressive data for lime-treated soils, are summarized in Table 12. The baseline information on untreated soils has been included as part of the data analysis.

The regression coefficients shown in Table 12 indicate that treating soils with lime tend to increase unconfined compressive strength, and that the increases are usually significant in the statistical sense. The major exception appears to lie with the Class IV fine-grained montmorillonitic soils, where lime is indicated as having a negative effect on strength. This observation contradicts the expectation that lime/montmorillonite combinations are stronger than those of montmorillonite alone.

It is not clear why the montmorillonite/lime systems behaved anomalously. Chemical analysis of the hydrated lime indicated about 85 to 90% calcium hydroxite, a range which should be sufficient for cementation. The problem may be related to specimen formulation. Air-dried soil and lime were thoroughly mixed and allowed to stand overnight. Water was added in the morning to bring the mixture to optimum moisture content. The soil/lime/water system was then allowed to mellow for about an hour prior to specimen compaction. It may be that the overnight contact between moisture in the air-dried soil and lime caused chemical changes in the soil which were reflected in lowered unconfined compression strengths.

The regression analysis results for the other three classes certainly indicate that lime does improve strength properties of soils, especially in the coarse-grained Class I and fine-grained Class III soils. In these cases, there is probably enough alumina in the clay fractions of the soils to combine with lime to produce cementation.

In the Class II soils, there are several which appear to be little affected by lime addition, e.g., Mahoning, Memphis, Shelby, Tama, and Wharton. In addition, the Coxville soil in Class I and Upshur series in Class III are indicated as unresponsive towards lime treatment. The Coxville series is kaolinitic, and its lack of response to lime treatment is expected.

As was observed with the sulfate waste-treated soils, moisture and curing time are relatively insignificant towards strength. In lime-treated soils, increased moisture tends to have a more positive effect on strength than it has in the untreated soils. Similarly, curing time has a tendency towards strength improvement. In general, ultimate strength appears to be achieved during the first few days of cure with lime treatment, and hence regression coefficients are small when forced into a linear representative with time.

In summary, lime tends to increase unconfined compressive strength of soils. Some soils, especially those with high argillaceous mineral content, require a greater amount of lime than others to achieve strength. When the soils respond to lime treatment, strengths are usually achieved during the first few days of cure.

D. Lime/Sulfate Waste-Treated Soils

The combination of lime and sulfate waste for treating soils has been shown to be quite effective in promoting unconfined compressive strength development. The unconfined compressive strengths of a number of soil/sulfate waste/lime systems have been evaluated and results analyzed using linear regression techniques. Results of the data analysis are presented in Table 13. As has been done in previous cases, the strength data obtained from the untreated soils, sulfate waste-treated soils, and lime-treated soils have been included in the data analysis in order to incorporate the appropriate zero reference points.

Treatment of soils with lime/sulfate waste generally is beneficial towards unconfined compressive strength. The magnitude of the sulfate waste coefficients and lime coefficients in Table 13 tends to be greater than the corresponding coefficients for sulfate waste alone (Table 11) or lime (Table 12) indicating a synergistic effect of the two materials. The effect is associated with the formation of cementitious calcium sulfoaluminate (ettringite) created by the reaction of lime, calcium sulfate (sulfate waste), and alumina (soil). All three ingredients are needed to produce ettringite, and hence one expects the strength increases which are observed.

The importance of sulfate is clearly demonstrated by the data. Use of phosphogypsum, a material containing about 30 to 40% sulfate, in conjunction with lime yields systems with greatly improved strength. On the other hand, use of flue gas desulfurization or neutralized acid mine drainage solid substances with much lower sulfate contents, does not appear to be as effective. A smaller amount of ettringite would be formed in the latter case, which would restrict strength development. Higher strengths could be achieved in these cases by increasing the amounts of both sulfate waste and lime used for treatment.

The strengths of coarse-grained Class I soils and Class II medium-grained soils are improved to a greater extent than those of the finer-grained soils. This improvement arises because the reaction products act basically as a cement to hold the coarse grains together. Following the data in Table 13 into the fine-grained Classes III and IV soils shows that the tendency towards strength improvement decreases. Class III non montmorillonitic soils are more responsive towards lime/sulfate waste treatment than are the Class IV montmorillonitic soils. This tendency is likely related to the need for a greater amount of lime treatment in the montmorillonitic soils. Thus, a higher ratio of lime to sulfate waste would be needed to stabilize montmorillonitic-type soils.

Soils which responded to neither lime nor sulfate waste treatment, e.g., Coxville (kaolinitic) and Mahoning (illitic), respond favorably to the combination of lime and sulfate waste. The degree of response depends upon the amount of sulfate in the waste, however. Thus, it appears that lime-soil reaction products will react further with calcium sulfate to produce a material with better strength properties than can be attained through conventional methods. We conclude, therefore, that many soils can be stabilized with a smaller quantity of lime, if some sulfate is present to promote strength formation.

As was noted with lime-treated soils, most of the strength developed in lime/sulfate waste-treated soils occurs within the first few days of cure. In general, strength development with time proceeds at a greater rate in lime/sulfate waste-treated soils than in the corresponding lime-treated systems. The rate of strength increase is again related to the amount of sulfate present in the waste, the high sulfate content phosphogypsum achieving strength more rapidly than the low sulfate content flue gas desulfurization and neutralized acid mine drainage solids.

In conclusion, unconfined compressive strengths of soils can be increased significantly by treatment with lime/sulfate waste combinations. The degree of improvement depends upon the sulfate content of the waste.

Greater strengths can be achieved using high sulfate content material than can be gained with low sulfate content wastes. Soils which respond to lime treatment tend to respond to lime/sulfate waste treatment. The amount of lime needed to achieve a given amount of strength can be lowered by including sulfate waste as part of the treatment. One should probably use a larger lime/sulfate waste ratio in fine-grained soils than is needed for coarse-grained soils.

E. Lime/Sulfate Waste/Fly Ash-Treated Soils

Eight soils, two from each of the four soil classes, were treated with ternary mixtures of lime, sulfate waste, and fly ash. The purpose of these tests was to determine the effects of fly ash on soil strengths when used in combination with lime/sulfate waste treatment. Unconfined compressive strength data for lime/sulfate waste/fly ash-treated soils have been reduced using linear regression analysis, results of which are shown in Table 14. Also included in the table are the lime/sulfate waste results for the comparable systems.

Six of the eight soils treated with lime/sulfate waste/fly ash mixtures show definite improvement with respect to strength formation over that achieved by lime/sulfate waste treatment alone. The two soils which did not respond to the ternary lime/sulfate waste/fly ash mixture are Fellowship and Sharpsburg, both of which are Class IV montmorillonitic soils. Thus, the well-established pattern of coarse-grained and fine-grained, nonmontmorillonitic responding favorably to lime/sulfate waste treatment is maintained for lime/sulfate waste/fly ash treatment. The nonresponse of the montmorillonitic soils cannot be explained.

The results shown in Table 14 indicate that fly ash addition is a bonus to strength formation for the cases where response is noted. The magnitude of the lime and sulfate waste coefficients in the ternary mixture with fly ash does not differ much from those of the binary mixture consisting of lime and sulfate waste alone. Thus, the fly ash does not affect the reaction between soil, lime, and sulfate waste; rather it behaves as an additional component which reacts with other available components to produce additional cementitious material.

In essence, the fly ash serves to provide active alumina to the system. As has been discussed earlier, alumina is an essential component for reaction with lime and sulfate waste to form ettringite, the calcium-sulfoaluminate which can give added unconfined compressive strength to soils. Because of the positive effect of fly ash on strength formation, the lime/sulfate waste reactions may prefer the alumina in the fly ash to that of the soils.

Curing time appears to be an important parameter in many of the finer-grained soils (Classes II, III, and IV). In one case, Fellowship series, strength appears to decrease with time for both the binary lime/sulfate waste system and the ternary lime/sulfate waste/fly ash systems. This negative dependence on time may mean that lime, which may have been insufficient for stabilizing Fellowship in the first place, is slowly withdrawn from ettringite thus destroying beneficial effects of the lime/sulfate waste treatment.

The sulfate wastes used in conjunction with fly ash were the phosphogypsums, high sulfate content materials. This choice was made to determine whether dilution of the high sulfate content by adding inorganic substances would tend to cause the soils to respond like those treated with flue gas desulfurization solids and lime. Results of the experiments indicate that such dilution does not alter basic properties of lime/phosphogypsum. We conclude, therefore, that there are substances other than fly ash in flue gas desulfurization solids which determine response to lime/flue gas desulfurization solids.

F. Cement/Sulfate Waste-Treated Soils

Four soils have been treated with portland cement and portland cement/sulfate waste to determine the effects of such treatment on unconfined compressive strength. The data from these tests have been analyzed, results of which are presented in Table 15. The four soils studied with cement include three Class I soils--Delray, Kendrick, and Norfolk--and one Class IV soil--Fellowship. The Fellowship series was chosen to see whether sulfate waste treatment would improve strength development in a relatively coarse-grained montmorillonitic soil.

The information in Table 15 indicates that inclusion of sulfate waste with cement may tend to degrade strength properties of soil/cement mixtures. Portland cement treatment by itself is, of course, an excellent method for stabilizing sandy soils. (The negative response of the Delray series in this respect is believed to be an anomaly due to insufficient sampling and perhaps to poor specimen fabrication.) When sulfate waste is added along with the cement, the effect of the cement on specimen strength remains essentially unchanged. The cement coefficients in both cement and cement/phosphogypsum-treated systems are within the respective standard deviations.

Addition of cement to the montmorillonitic Fellowship series yielded strengths similar to those achieved with lime treatment. The lesser amount of lime available in portland cement may be a reason for the smaller regression coefficient in the portland cement system. Apparently, a larger amount of lime is needed for increasing strengths of the Fellowship series, and neither 6% lime nor 6% cement is sufficient. The addition of phosphogypsum to either of these additives does not benefit strength development to any significant extent.

Time does not seem to be a significant factor in strength development. Most of the strength achieved in soil/cement (or soil/cement/sulfate waste) systems is gained in the first few days of cure. The addition of phosphogypsum does not appear to retard strength development.

On the basis of these limited number of tests, we conclude that portland cement/phosphogypsum mixtures are not particularly attractive. Strengths of soils which are stabilized with portland cement cannot be improved by the addition of phosphogypsum. If any effect is achieved by adding the sulfate waste, it is likely to decrease in strength.

G. Kiln Dust/Sulfate Waste-Treated Soils

The final series of tests undertaken on the program involved the treatment of soils with cement kiln dust and cement kiln dust/sulfate waste mixtures. Cement kiln dust is a by-product of portland cement manufacturers and represents a finely divided mixture of calcined lime and raw cement feed which is collected at the feed end of a rotary kiln. In addition, the dust contains alkali (sodium and potassium) oxides volatilized in the burning process. In many cases, the alkali content of the dust is too high to permit its recycle into portland cement product. The Portland Cement Association indicates that as much as 60% of the dust (about 3 to 4 million tons per year nationwide) cannot be recycled because of alkali restrictions on portland cement.

Because the kiln dust contains a large amount of free calcium and alkali oxides, it was considered as a lime substitute for sufate waste/lime systems. Eight soils were evaluated with respect to kiln dust and kiln dust/sulfate waste treatment. Unconfined compressive strength data for specimens treated with kiln dust and kiln dust/sufate waste have been analyzed by linear regression. The regression coefficients, standard deviations and statistical significances are shown in Table 16. The sulfate wastes used in these experiments were flue gas desulfurization solids from Kansas (FG2) and neutralized acid mine drainage solids from Pennsylvania (AMD).

In general, kiln dust alone is an adequate material for soil stabilization. Seven of the eight soils tested responded positively to kiln dust addition. The degree of response is somewhat greater than the corresponding responses in the lime-treated systems. It is believed that the greater strengths achieved with the kiln dust-treated soils is due to sulfate present in the kiln dust. In addition to alkali oxides, cement kiln dust also contains minor amounts of sulfate (normally 3 to 7%) due to reaction between the dust and sulfur oxides generated by burning coal in the cement manufacturing process. The sulfate will react with the lime and clay also in the dust to produce ettringite. Because all of these materials are present together, one has a mixture similar to that of lime/phosphogypsum/fly ash described earlier which also gave excellent strengths when mixed with soil. Since the kiln dust contains about 50% inert unburnt limestone, the very high strengths of the lime/phosphogypsum/fly ash system are not achieved.

The addition of sulfate waste to the kiln dust does not have a major effect on strength development in most cases. However, in the one case (Higginsville) in which the soil responded negatively to kiln dust treatment, the soil responded positively when treated with kiln dust and FG2. The combination treatment showed a significant positive effect for both the kiln dust and the sulfate waste. A similar synergism was also observed inthe Summit series. For the case of the Sharpsburg/FG2 system, inclusion of sulfate waste with kiln dust resulted in offsetting effects. The kiln dust gave a larger regression coefficient when mixed with FG2 than it did with the kiln dust alone. However, the improved effect of kiln dust in the mixture was offset by the negative regression coefficient associated with the FG2.

Time does not seem to be a major factor for developing strength in soils treated with kiln dust or kiln dust/sulfate waste. Strengths are developed early in the curing period, an observation also made in the lime related systems.

In summary, kiln dust by itself seems to be an excellent material for soil stabilization in its own right. Much of its excellence can be traced to the small quantities of sulfate in the kiln dust. Sulfate wastes (as represented by flue gas desulfurization and neutralized acid mine drainage solids) do not greatly affect strengths developed in kiln dust treated soils. However, there occasionally may be cases where a definite synergism between kiln dust and sulfate waste exists.

H. Durability/Stability Studies

A few selected soil/sulfate systems have been evaluated with respect to freeze-thaw stability and shrink-swell potential. Results of these experiments indicate that the addition of sulfate waste has little effect on the freeze-thaw properties. In the case of free-thaw stability, several soil/lime/sulfate waste systems were also evaluated. and results suggest that the freeze-thaw stability parallels that expected in soil/lime systems, i.e., the sulfate waste has little effect. In the case of shrink-swell, we have found that shrink-swell potential tends to be increased when sulfate waste is added to soils which are sensitive to sulfate in the untreated state. On the other hand, addition of sulfate waste to soils which are not prone to shrink-swell does not appear to affect valume stability. Discussion of these experiments follows.

1. Freeze-thaw stability - Freeze-thaw stability measurements have been made using the vacuum/saturation technique developed by Dempsey and Thompson.[1/] This technique consists of exposing cured specimens to a vacuum (-24 in. of mercury) for 30 min. Following the vacuum treatment, water is introduced into the chamber sufficient to flood the specimens. The specimens are then soaked for 1 hr at atmospheric pressure. At the end of the soak period, excess water is allowed to drain from the specimens which are then immediately tested for unconfined compressive strength.

For the study reported herein, we cured the soil/sulfate waste and soil/sulfate waste/lime specimens for 7 days. The specimens were prepared and cured using the same techniques as for unconfined compressive strength testing, i.e., the specimens were wrapped in Saran wrap and cured at 100% humidity and 73°F. Following the vacuum saturation treatment, unconfined

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1/ Dempsey, B. J., and M. R. Thompson, "A Vacuum Saturation Method for Predicting the Freeze-Thaw Durability of Stabilized Materials," Highway Research Record No. 442, 44-57 (1973).

compressive strength tests were conducted and moisture determined in the sacrificed specimen. Results of the freeze-thaw experiments are presented in Table 17. Included also in the table are the 28 day unconfined compressive strength data of the comparable systems. A percentage comparison of compressive strength and moisture contents of specimens to the 28-day "control" specimens is also presented.

The data in Table 17 clearly indicates that the soil/sulfate waste/lime systems are more durable with respect to freeze-thaw than are the soil/sulfate waste systems. The strength decreases in the lime/sulfate systems are much less than those of the sulfate waste-treated systems. It appears that the Mahoning-PG3 system is least affected by freeze-thaw, while the Wharton AMD system is most affected. These results suggest that the lime is primarily responsible for freeze-thaw stability.

Moisture content, on the other hand, tends to be greater in the lime/sulfate waste-treated soils after vacuum saturation treatment than in the sulfate waste-treated systems. These higher moisture contents are not associated with decreased strengths as might be expected. The two cases in which the moisture content did not increase as much are the Sharpsburg-AMD and Wharton AMD systems in which only 2% lime was used for the soil/sulfate waste/lime specimens, suggesting that lime content affects moisture-holding characteristics of soils.

The freeze-thaw durability experiments point out the importance of lime addition if sulfate waste is used. As has been described earlier, lime-sulfate waste treatment is essential for strength development in soils. The results described have suggested that lime also serves an additional function--to promote durability in the stabilized soils.

2. Volume stability - Volume stability of selected soil sulfate waste systems was measured using a modification of procedures described by Abercrombie.[1/] The modifications consisted of (a) the use of molds for the Harvard Miniature Compaction Apparatus, and (b) use of a vernier caliper for measuring. Specimen preparation, cure, and volume change were all determined as described in the procedure. Results of the volume stability experiments are shown in Table 18, together with reported shrink-swell characteristics of untreated soils.

1/ Abercrombie, W. F., "Suggested Method of Test for Volume Change of Soils," in ASTM Special Technical Publication 479, Special Procedures for Testing Soil and Rock for Engineering Purposes, 5th Ed., American Society for Testing and Materials, Philadelphia, 383-384 (1970).

From the information in Table 18, it appears that addition of sulfate waste generally may tend to increase shrink-swell potential of soils. The shrink-swell of the Katy and Shelby series is "very high" (volume change 6%) in the sulfate waste treated systems, while it is reported as "moderate" (volume change 2 to 4%) in the untreated soils. Likewise, the shrink-swell rating of the Summit series, a montmorillonitic soil, is "very high" in the FG2 treated system, while it is only "high" in the untreated soil. Shrink-swell potential in two medium grained Class II soils--Exum and Mahoning--does not appear to be greatly affected by the addition of sulfate waste. Thus, we conclude that in cases where sulfate waste addition does affect shrink-swell potential of soils, the effect is probably going to adverse.

The results obtained with the sulfate waste treated soils are consistent with other studies. Sulfate has long been known to increase shrink-swell potential in soils because of its ability to hold water causing swelling when wet and shrinkage when dry. The adverse affects of the sulfate/moisture relationships can be minimized, however, if one uses lime in conjunction with the sulfate. The combination of lime, sulfate, and aluminum (from the soil) will produce ettringite, a hydrated calcium sulfo-aluminate which prevents excess shrinkage. The formation of ettringite is the basis for expansive cements which can be used to prevent shrinkage cracking in concrete. Thus, the inclusion of lime along with sulfate waste should significantly reduce adverse shrink-swell effects arising from sulfate waste treatment of soils.

IV. DISCUSSION OF UNCONFINED COMPRESSIVE STRENGTH TEST RESULTS

A. Class I Soils: Plasticity Index NP-10

This section discusses the results of the unconfined compressive strength tests for the Class I soils. It is arranged on a soil-by-soil basis, and presents the specific details leading to the conclusions and generalizations discussed earlier in the report. The results of the linear regression analysis for unconfined compressive strength data (as shown in Tables 10 through 16) have been reordered on a soil-by-soil basis allowing direct comparison of the different types of treatment on strength properties. In addition, the linear equations arising from the regression analysis have been plotted as a function of curing time for the various systems evaluated in the program.

The plots presented in the subsequent discussion assume that strength is developed linearly with time, an obvious oversimplification. The principal purposes of the plots are to give a general idea of how the soils respond to various differences within the first 28 days of cure, and to indicate the magnitude of differences. Thus, they cannot be extrapolated to long times to predict "ultimate" strengths.

The moisture contents used to establish the straight lines in the figures are the average values for each system plotted. In addition, one sulfate waste concentration (6%) is assumed. The treatment levels of additives to the sulfate wastes (lime, cement, fly ash, and cement kiln dust) are all 2%.

Atterberg Limits and moisture-density relationships of the soil/sulfate waste systems are presented in Part A of Appendix B to this report. The raw data obtained for unconfined compressive strength and moisture content of specimens, which was used for the linear regression analysis, are given in Part A of Appendix C.

The Class I soil/sulfate waste systems discussed below are:

1. Atkins Series

   FGl
   AMD

2. Charlton Series

   Lime
   FGl/lime
   AMD

3. Convent Series

   Lime
   PG1/Lime
   PG3

4. Coxville Series

   Lime
   PG2
   PG2/Lime
   PG2/Lime/Fly Ash

5. Delray Series

   Cement
   PG1
   PG1/Cement

6. Hazelton Series

   Lime
   Kiln Dust
   FG1
   FG1/Lime
   AMD
   AMD/Lime
   AMD/Kiln Dust

7. Kendrick Series

   Cement
   PG1
   PG1/Cement

8. Manor Series

   Lime
   Kiln Dust
   FG1/Lime
   AMD
   AMD/Lime
   AMD/Kiln Dust

9. Norfolk Series

Lime
Cement
PG1/Lime
PG1/Cement
PG2

10. Prentiss Series

Lime
PG2
PG3
PG3/Lime
PG3/Lime/Fly Ash

11. Wagram Series

PG2

1. Atkins series - The Atkins soil series is a member of the fine-loamy, mixed, acid, mesic family of Typic Fluvaquents, and consists of deep, poorly-drained soils on flood plains. The soil is classified as A-2 to A-6 in the AASHTO System. The soil is considered to be a poor source for road fill because of excessive moisture and a high water table. The Atkins series is of large extent and is found in Indiana, Kentucky, Maryland, Missouri, Ohio, Oklahoma, Pennsylvania, Tennessee, Virginia, and West Virginia. The type location is in Raleigh County, West Virginia. The sample used for the experimental study was obtained at the type location. The AASHTO classification of the soil sample was A-4.

Two sulfate wastes--Illinois flue gas desulfurization solids and Pennsylvania neutralized acid mine drainage solids--were evaluated with respect to their effects on the unconfined compressive strength of the Atkins soil series. The effects of 6% addition of the two sulfate wastes are plotted in Figure 4. Regression analysis of the unconfined compressive strength data is shown in Table 19.

The data indicate that the addition of both FG1 and AMD improves the strength of the Atkins soil. However, the statistical significance of the sulfate waste coefficients is below the 90% level, raising some doubts as to the real degree of strength improvement.

Moisture may have a negative effect on the unadulterated Atkins soils. As sulfate waste is added, the degree of the moisture effect becomes less, indicating that the sulfate waste provides fines to fill the voids in the relatively coarse soil when compacted.

Curing time has little effect on the Atkins soil/sulfate waste systems. Strengths in the FGl system decrease slowly with time. However, increased moisture is a more significant factor in loss of strength than is curing time for this particular system.

2. Charlton series - The Charlton series is a member of the coarse-loamy, mixed, mesic family of Entic Haplorthods. It consists of deep, well-drained soils found on uplands, and is classified A-2 and A-4 in the AASHTO Scheme. This soil is nonplastic, and is good source material for road fill. The Charlton series is of large extent and is found in Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont. The soil sample used in the study was obtained from the type location in New Haven County, Connecticut. The AASHTO classification of the soil sample was A-4.

The Charlton series was evaluated in conjunction with the FGl and AMD sulfate wastes. In addition, lime was included in the Charlton/FGl system. The effects of 6% FGl addition and 6% FGl-2% lime addition on unconfined compressive strengths of Charlton soil are plotted in Figure 5; that of 6% AMD addition is shown in Figure 6. Results of the linear regression analysis of the Charlton series systems are summarized in Table 20.

Addition of sulfate waste to the Charlton series increases unconfined compressive strength, especially in combination with lime. The effect is particularly noted in the Charlton/PGl/lime system. On the other hand, the Charlton soil responds negatively to lime addition with respect to strength. The negative response to lime is offset when the lime is mixed with FGl.

Excess moisture is detrimental to strength development with the Charlton series in both the unadulterated soil and with the lime/soil system. The deleterious effects of moisture are diminished somewhat when either FGl or AMD is added to the soil. Curing time is not a significant factor with regard to strength.

The mixture of FGl with lime, especially where the FGl is in excess, will cause substantial increases in unconfined compressive strengths of the Charlton soil series. The addition of the AMD waste does little for strength development.

3. Convent series - The Convent series is a member of the coarse-silty, mixed, nonacid, thermic family of Aeric Fluvaquents. The soil is formed in loamy alluvial deposits from the Mississippi River, and is somewhat poorly drained and moderately permeable. The AASHTO classification of the Convent soil is A-4. It is fairly suitable for road fill, but tends to be wet and of low strength. The Convent series is of moderate to large extent and is found throughout the Lower Mississippi River flood plain in Arkansas, Mississippi, Louisiana, and Tennessee, and possibly as far north as Kentucky and Missouri. The type location of the Convent series is in St. John the Baptist Parish, Louisiana. The sample used for study was obtained in St. James Parish, Louisiana, and its AASHTO classification was A-4.

The sulfate wastes studied with the Convent series include two phosphogypsums--PG1 and PG3. The PG1/lime system is plotted in Figure 7, and the PG3 system in Figure 8. Results of the linear regression analysis of unconfined compressive strength data are shown in Table 21.

The Convent soil is unresponsive with respect to unconfined compressive strength development when mixed with phosphogypsum (PG3) alone. However, when phosphogypsum (PG1) and lime are both mixed with the soil, strength development is considerably enhanced.

The important parameters associated with strength development in the lime-phosphogypsum systems are lime and curing time. In the absence of the phosphogypsum, both lime and curing time are highly significant with respect to ultimate strength development. The magnitude of these parameters becomes even greater when the phosphogypsum is added. Thus, we conclude that lime-phosphogypsum mixtures are quite effective in promoting strength development with the Convent soils.

The moisture parameter does not appear to be an important factor with regard to strength. It is significant at the 90% level in the Convent/lime system, but not significant for all others. The validity of the high moisture coefficient in the Convent/PG1/lime system (7.55) is subject to considerable doubt because of the size of the standard deviation (7.73).

4. Coxville series - The Coxville series is a member of the clayey, kaolinitic, thermic family of Typic Paleaquults, and consists of deep, nearly level, poorly-drained soils on the Southeastern Coastal plain. The AASHTO classifications of the Coxville soils range from A-4 to A-7.

The soil is rated poor with respect to its usage as road fill because of wetness. The Coxville series is of large extent and is found in the Coastal plain of Alabama, Florida, Georgia, Mississippi, and North Carolina, and possibly in Louisiana and Virginia. The type location is in Pitt County, North Carolina, which was also the site at which the experimental sample was collected. The sample of Coxville soil had an AASHTO classification of A-4.

Since the Coxville series was the only kaolinitic soil investigated, it was evaluated with respect to several combinations of additives. The sulfate waste used in the studies was phosphogypsum PG2 from North Carolina. The effects of mixing the phosphogypsum with lime and fly ash have also been investigated. Plots of the unconfined compressive strength-curing time relationships of several Coxville systems are shown in Figure 9, and the results of the linear regression analysis of unconfined compressive strength data are given in Table 22.

As can be seen from Figure 9 and Table 22, strengths of the Coxville soil are not affected by either sulfate waste or lime addition. The addition of PG2 may have a minor deleterious effect on the strength development. However, the effect is small and cannot be distinguished from the effects of the soil alone.

Unlike other soil/phosphogypsum systems, strength development is not greatly affected when the phosphogypsum is mixed with lime. In the Coxville/PG2/lime system, the magnitude of sulfate waste coefficient is increased to +2.34, compared to -0.50 in the Coxville/PG2 system. Similarly, the lime coefficient in the Coxville/PG2/lime system is +8.98, whereas it is only +2.96 in the Coxville/lime system. However, the moisture coefficients are negative in the mixed systems compared to the untreated soil, and offset the positive effects of sulfate waste/lime addition.

On the other hand, when fly ash is added to the phosphogypsum and lime to produce a stabilization agent, strength development increases markedly. The strength characteristics in the Coxville/PG2/lime/fly ash system are dominated by the effect of the fly ash itself. The negative effect of moisture is overcome by the greater positive effect of fly ash. Thus, we conclude that unconfined compressive strength of the Coxville series (and perhaps of other kaolinitic soils) can be increased significantly by incorporating lime-phosphogypsum-fly-ash mixtures into the soils.

The data in Table 22 indicate that addition of lime, phosphogypsum, and fly ash also markedly affect the moisture requirements of the compacted soils. The moisture coefficients in the Coxville/PG2/lime and Coxville/PG2/lime/fly ash systems are negative and statistically significant. These observations are interpreted to mean that one would work

below optimum moisture content, when either the binary lime/phosphogypsum or the ternary lime/phosphogypsum/fly ash additives were being used.

5. Delray series - The Delray series is a member of the loamy, mixed, noncalcareous, hyperthermic family of Grossarenic Argiaquolls, and consists of poorly-drained soils in the Lower Coastal Plain. Because they are associated with high water tables, runoff is slow although permeability is rapid. This soil series is of moderate extent and is found in the Florida peninsula. The sample used for the experimental program was obtained near the type location in Okeechobee County, Florida, and had an AASHTO classification of A-4.

The Delray series has been evaluated with respect to the Florida phosphogypsum (PG1), and with respect to portland cement-PG1 mixtures. The unconfined compressive strengths as a function of time are plotted in Figure 10, and results of the linear regression analysis summarized in Table 23.

As can be seen in Figure 10, strengths of the Delray series are increased when either cement or cement-phosphogypsum is added to the soil. The addition of 6% PG1 has virtually no effect on soil strength.

The moisture and cement regression coefficients in Table 23 for the Delray/cement system are questionable, despite the fact that they are statistically significant. The number of samples used for this system is small (only 10), and it appears that they may have been too wet when they were formulated. However, we observe a large negative moisture coefficient (-8.77) which could tend to diminish the cement coefficient also.

When a greater number of specimens are included for the Delray/PG1 system, the regression coefficients in Table 23 become more reasonable. In this system, the cement coefficient is positive as would be expected, although it is not as large as might be expected. However, the cement coefficient is significant at the 99.9% confidence level so its importance is real. The smallness of the cement coefficient in the Delray/PG1/cement system is thus interpreted as reflecting the tendency of phosphogypsum/cement systems to be less effective than phosphogypsum/lime systems towards soil stabilization.

6. Hazelton series - The Hazelton series is a member of the loamy-skeletal, mixed, mesic family of Typic Dystrochrepts. The series consists of deep, well-drained soils on uplands. The Hazelton soil is a coarse-grained soil, and its AASHTO classifications range from A-1 to A-4.

It is a fair source material for road fill being moderately affected by frost action. The Hazelton series is of large extent and is found in Kentucky, Maryland, New Jersey, Pennsylvania, West Virginia, and perhaps in Ohio and Virginia. The type location is in Warren County, Pennsylvania. The sample obtained for the experimental program was obtained near the type location. The AASHTO classification of the Hazelton sample was borderline between A-2-4 and A-4.

The effect of two sulfate wastes on the unconfined compressive strength of the Hazelton soil has been studied. The two sulfate wastes are FGl and AMD. In addition, the effects of lime have been evaluated in the soil/sulfate waste systems. For the case of the AMD systems, cement kiln dust was also evaluated as a substitute for lime. The unconfined compressive strength versus curing time plots for the Hazelton/FGl systems are shown in Figure 11, and those for the Hazelton/AMD systems in Figure 12. The linear regression coefficients, standard deviations, and significances are presented in Table 24.

The FGl systems plotted in Figure 11 indicate that FGl has little effect on the ultimate unconfined compressive strength of Hazelton soils. The significant positive dependence of FGl as indicated in Table 24 is offset by the significant negative dependence of moisture. Thus, the two effects tend to cancel each other. However, if one used the flue gas waste under moisture conditions less than optimum, an improvement in strength might be achieved.

A more likely alternative would be to incorporate lime into the soil/FGl system. The data indicate clearly that lime alone will enhance strength development, but that the combination of lime and FGl tends to increase strengths even more. The FGl coefficient increases from +0.65 in the FGl system to +2.65 in the FGl/system. Similarly, the lime coefficient increases from +2.33 in the lime system to +5.66 in the FGl/lime system. Thus, one concludes that the use of flue gas desulfurization waste in combination with small amounts of lime will indeed cause significant strength increases in Hazelton soils.

A similar pattern is followed in the Hazelton/AMD systems, although the effects are not as pronounced. The combination of lime-AMD yields unconfined compressive strengths greater than those obtained with either lime or AMD alone.

When cement kiln dust is used, however, the strengths are greater than those obtained with equivalent amounts of lime. The Hazelton/kiln dust system yields strengths of the same magnitude as those for the soil/AMD/lime system. Strengths can be increased further by incorporating AMD waste into the soil/kiln dust systems. From the data in Table 24, it would appear that the utility of the kiln dust is enhanced considerably by the addition of fairly large additions (6 to 12%) of the AMD material.

7. Kendrick series - The Kendrick series is a member of the loamy, siliceous, hyperthermic family of Arenic Paleudults, and consists of well-drained soils on the coastal plain in Central Florida. The properties fall in the range of A-2 to A-4 in the AASHTO classification scheme. The Kendrick soil is a fair material for road fill, although it normally exhibits low strengths. The soil is located in the Florida peninsula primarily on the Ocala uplift from Hillsborough through Alachua Counties, and is moderately extensive throughout this area. The soil sample used for the study was obtained near the type location in Marion County, Florida, and its AASHTO classification was A-4.

The Kendrick series has been evaluated with respect to the Florida phosphogypsum (PG1). Portland cement has been evaluated as an additive to the phosphogypsum. The unconfined compressive strengths of Kendrick/PG1 systems have been plotted as a function of curing time in Figure 13. Results of the data analysis for the systems are given in Table 25.

The use of phosphogypsum with Kendrick soil tends to result in a minor increase of unconfined compressive strength. However, the increased strength is achieved by working at moisture contents less than optimum. Too much moisture tends to degrade strength properties of Kendrick/PG1 mixtures.

Strengths can be increased further by adding small quantities of portland cement to the soil-phosphogypsum mixtures. Strengths achieved in the soil/phosphogypsum/cement system are somewhat less than those of the soil/cement system. The negative coefficient of the PG1 component in the Kendrick/PG1/cement system indicates that phosphogypsum/cement mixtures are not particularly effective with the Kendrick soil. Thus, one would probably not use phosphogypsum/cement stabilization for this soil, but would consider straight portland cement stabilization instead.

8. Manor series - The Manor series is a member of the coarse-loamy, micaceous, mesic family of Typic Dystrochrepts, and occupies strongly dissected uplands in the northern Piedmont plateau. The soil is well drained and permeability is moderate to rapid. The Manor series is of large extent and commonly dominates the landscape in the mid-Atlantic states. The soil is found in Delaware, the District of Columbia, Maryland, Pennsylvania, Virginia, and possibly North Carolina. The type location is in Prince Georges County, Maryland, where the soil sample used for the study was obtained. The Manor sample had an AASHTO classification of A-4.

The Manor series has been evaluated with two sulfate wastes--flue gas desulfurization solids (FG1) and neutralized acid mine drainage solids (AMD). The response of strengths to binary combination of lime/sulfate waste has also been ascertained, as has been the binary combination of cement kiln dust and AMD. The Manor/FG1 systems are plotted in Figure 14 and the Manor/AMD systems in Figure 15. The results of unconfined compressive strength data analysis are presented in Table 26.

The Manor/FG1 systems plotted in Figure 14 indicate that lime has little effect on unconfined compressive strengths, whereas the lime-FG1 mixtures result in substantial strength improvement. The lime systems do appear to gain strength slowly, however. The important feature of the data lies in the lime-FG1 systems, since the combination of the two ingredients appears to be of significant benefit in promoting strength development.

A similar situation is noted with regard to the AMD systems. Neither lime nor AMD alone is effective for strength improvement in the Manor soil. However, the combination of lime and AMD again results in substantial improvement of strengths. When cement kiln dust is used as a substitute for lime, strengths can be improved even more. The use of kiln dust alone tends to result in strength increases greater than those obtained for the lime-AMD systems. When kiln dust and AMD are used in combination, the strengths are increased even further.

The strengths in the Manor/AMD/lime and Manor/AMD/kiln dust systems are somewhat less than those developed in the Manor/FG1/lime systems. These phenomena are probably due to the greater sulfate content of the FG1 component (about 13% compared to about 2% in the AMD). The combination of sulfate and lime consistently leads to improved strength development. The strengths of AMD/kiln dust systems in turn may be a consequence of the sulfate content in the kiln dust which normally is about 5%.

9. Norfolk series - The Norfolk series is a member of the fine-loamy, siliceous, thermic family of Typic Paleudults, and consists of well-drained soils in the upland coastal plain. The AASHTO classification of the soil ranges from A-2 in the topsoil to A-6 in the subsoil. The soil is a good source material for road fill. The extent of the Norfolk series is large and is found in the coastal plain areas of Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Texas, and Virginia. The sample acquired for investigation was obtained near the type location in Robeson County, North Carolina. The AASHTO classification of the sample was borderline between A-2-4 and A-4.

The effects of two phosphogypsums--PG1 from Florida and PG2 from North Carolina--have been determined with respect to strength development in the Norfolk series. The PG1 material has been evaluated further when mixed with either lime or portland cement to make a binary soil stabilizer. The Norfolk/PG1 system strengths are plotted in Figure 16, and the Norfolk/PG2 system in Figure 17. The linear regression analysis results of the unconfined compressive strengths data are given in Table 27.

The effect of phosphogypsum (PG2) alone on strengths of the Norfolk soil is negligible. When the soil is treated with lime, strength develops more rapidly and within a few days is much improved over that of untreated soil. The use of portland cement as a stabilizer results in immediate and dramatic strength improvement.

The addition of phosphogypsum (PG1) to either lime or cement for stabilization tends to degrade the strengths that can be achieved by using lime or cement alone. This effect with cement has been noted in other soil systems (Delray and Kendrick). The effect with lime, however, may be due to the silica content of the Norfolk soil. In order for lime-sulfate combinations to promote stability, a third ingredient is needed--alumina. If sufficient alumina is not present in the soil, then the lime-sulfate-alumina compounds (ettringite-like materials) which give strength to the systems cannot be formed. Hence, the advantages of using sulfate waste in conjunction with lime cannot be achieved. Thus, we conclude that phosphogypsum-lime combinations should be considered in cases where reactive alumina content of soils is available for formation of ettringite The soil would probably need a minimum of 15 to 20% alumina for reaction with lime and sulfate.

10. Prentiss series - The Prentiss series is a member of the coarse-loamy, siliceous, thermic family of Glossic Fragiudults. The series consists of moderately well-drained soils with fragipans, and is classified A-4 to A-6 in the AASHTO system. The soil is a fair material for road fill, but has less than desirable strength. The Prentiss series is found in Alabama, Arkansas, Louisiana, Mississippi, and Tennessee and is moderately extensive. The type location for the series is in Loundes County, Mississippi. The soil sample used for the experimental work was collected in St. Tammany Parish, Louisiana. The AASHTO classification of the Prentiss sample was A-4.

Two phosphogypsums were studied to determine their effects on strength development of the Prentiss soil: PG2 from North Carolina and PG3 from Texas. In addition, the PG3 systems were evaluated in conjunction with lime and lime-fly ash mixtures. The strength development with time of the Prentiss/PG2 system is shown in Figure 18, and of the Prentiss/PG3 systems in Figure 19. Table 28 contains the results of linear regression analysis of unconfined compressive strength data for all of the Prentiss/phosphogypsum systems.

As has been noted in other systems involving phosphogypsum alone, unconfined compressive strengths in soil/phosphogypsum mixtures are little different from those of the untreated soil. However, strenghts are improved substantially when lime is added to the phosphogypsum. The addition of fly ash to the phosphogypsum-lime mixtures tends to increase strengths even further, probably because the fly ash contains alumina available for the formation of sulfoaluminate stabilizing materials.

The strength improvement in the Prentiss/lime and Prentiss/PG3/lime systems over that of the control sample may indicate that the Prentiss soil has a greater quantity of agrillaceous (alumina-containing) material than does the Norfolk soil discussed earlier, despite the fact that both are classified as siliceous. This observation suggests that one cannot rely exclusively upon soil descriptive information to determine whether strengths of a particular soil are responsive to lime-phosphogypsum treatment. Experimental tests would be needed to determine the degree of response to such treatment.

11. Wagram series - The Wagram series is a member of the loamy, siliceous, thermic family of Arenic Paleudults, and consists of well-drained soils with sandy surface layers 20 to 40 in. thick over sandy clay loam subsoils. The surface horizon of the Wagram series is classified A-2 in the AASHTO system, while subsurface horizons contain materials falling into A-6 and A-7 categories. The soil is a good source material for road fill. The series is of large extent and found throughout the Atlantic and Gulf coastal plains from Texas to Virginia. The type location for the Wagram series is in Scotland County, North Carolina. The sample used for study was obtained near the type location and had an AASHTO classification of between A-2-4 and A-4.

Strengths of the Wagram series were evaluated with respect to the North Carolina phosphogypsum (PG2). Strength development as a function of curing time is shown in Figure 20, and results of the data analysis summarized in Table 29.

The results of the testing of Wagram/PG2 systems follow a predictable pattern. The addition of phosphogypsum to the soil does not generate much improvement in strength over that obtained in the untreated soil. The analysis of data in Table 28 indicates that the inclusion of phosphogypsum is significant with respect to strength increase. However, the sulfate waste coefficient is small (only +0.74) and most of the improvement is noted at early stages.

The response of the Wagram soil to phosphogypsum would probably be favorable if lime or lime-fly ash was mixed with the phosphogypsum. This expectation is based upon extrapolation of results for similar soils discussed earlier, e.g., Norfolk and Prentiss.

B. Class II Soils: Plasticity Index 10-25

The following discussion presents interpretation of findings for Class II soils related to unconfined compressive strength changes caused by treating soils with sulfate wastes and mixtures involving sulfate waste. The discussion is organized on a soil-by-soil basis.

The figures used in the subsequent discussions were developed from the linear regression analysis of unconfined compressive strength data. The average moisture content of each soil was used in conjunction with a 6% addition of sulfate waste, and in many cases a 2% addition of lime, cement kiln dust, or fly ash. The resulting equations are a function of curing time, and the strength versus time relationships have then been plotted. The tables presented have been developed by compiling the entries in Tables 10 through 16 discussed earlier in this report on a soil-by-soil basis.

Atterberg Limit and moisture-density relationships for the Class II soils are presented in Part B of Appendix B. Raw data for unconfined compressive strengths and moisture contents which were used for the linear regression analysis from which figures and tables have been developed are presented in Part B of Appendix C.

Soil series in the Class II category which will be discussed in this section include:

1. Commerce Series

   Lime
   PG1/Lime
   PG1/Lime/Fly Ash
   PG3

2. Exum Series

   Lime
   PG2
   PG2/Lime

3. Mahoning Series

   Lime
   Kiln Dust
   PG3
   PG3/Lime
   PG3/Lime/Fly Ash
   PG1
   PG1/Lime
   AMD
   AMD/Lime
   AMD/Kiln Dust

4. Memphis Series
   Lime
   PG1/Lime
   PG3

5. Miami Series

   Lime
   PG2
   FG1/Lime
   AMD

6. Sassafras Series

   Lime
   FG1
   FG1/Lime
   AMD
   AMD/Lime

7. Shelby

   Lime
   Kiln Dust
   FG2
   FG2/Lime
   FG2/Kiln Dust
   AMD
   AMD/lime

8. Tama Series

Lime
PG3
PG3/Lime
FG1/Lime
AMD
AMD/Lime

9. Wharton Series

Lime
Kiln Dust
FG1/Lime
AMD
AMD/Lime
AmD/Kiln Dust

1. Commerce series - The Commerce series is a member of the fine-silty, mixed, nonacid, thermic family of Aeric Fluvaquents, and consists of somewhat poorly drained, moderately slowly permeable soils. The AASHTO classification of the Commerce series ranges from A-4 to A-7-6. The soil is considered to be a fair source material for road fill, but often exhibits low strength, has moderate potential for shrink-swell, and is wet. The Commerce series is of large extent and found throughout the lower Mississippi River flood plain in Arkansas, Louisiana, Mississippi, Missouri, and Tennessee. The type location is in Tensas Parish, Louisiana, where the sample for laboratory investigation was obtained. The Commerce sample had an AASHTO classification of A-6.

The effect of two phosphogypsums on the unconfined compressive strengths of the Commerce soil has been studied: PG1 from Florida and PG3 from Texas. The Commerce/PG1 systems were also evaluated with respect to the additives lime and lime-fly ash. Unconfined compressive strength versus time plots are given in Figure 21 for the Commerce/PG1 systems, and in Figure 22 for the Commerce/PG3 system. Results of the linear regression analyses are presented in Table 30.

Both phosphogypsums appear to enhance strengths of the Commerce soil. When it is used alone (PG3) at a 6% level, the strengths are increased by about 10% over those of the untreated soil. When 6% PG1 and 2% lime are used, the initial strength is almost 25% greater than the untreated soil. In the latter case, however, strength increases fairly rapidly and is more than double that of untreated soil at 28 days.

The combination of lime and phosphogypsum is much more effective than lime alone, indicating that the Commerce soil probably has alumina-bearing components. The addition of more alumina in the form of fly ash yields even greater strength. Thus, we conclude that lime-phosphogypsum and lime-phosphogypsum-fly ash mixtures would be excellent agents for stabilizing Commerce and similar soils.

2. Exum series - The Exum series is a member of the fine-silty, siliceous, thermic family of Quic Paleudults, and consists of moderately well-drained soils as the upland Atlantic coastal plain. The AASHTO classification of the soil ranges from A-4 to A-6. The soil is fairly suitable as a source of road fill but has a tendency towards wetness. The Exum series is moderately extensive and is found in the coastal plains of North Carolina, South Carolina, and Virginia. The sample acquired for the study was collected near the type location in Wayne County, North Carolina, and had an AASHTO classification of A-6.

The response of the Exum soil to the North Carolina phosphogypsum (PG2) was evaluated. In addition, the soil was intermixed with lime/phosphogypsum mixtures to evaluate the effect on strength. The strength versus time plots are presented in Figure 23, and the results of the linear regression analyses of strength data are given in Table 31.

Unconfined compressive strength is affected little by adding PG2 to the Exum soil. Strengths can be improved by treating the soil with lime. However, the treatment using a combination of both PG2 and lime yields a marked improvement over that obtained with lime over the long term.

The lime/PG2 effects on the strength of Exum soil suggest that the soil contains some argillaceous components which are available for the formation of calcium sulfoaluminate (ettringite). The major mineral in the Exum series is reported to be silica, a substance which is nonreactive towards lime and sulfate. The fact that the Exum series responds favorably to lime/sulfate waste indicates that primary soil minerology is not sufficient to predict behavior of specific soils towards lime/sulfate waste treatment.

3. Mahoning series - The Mahoning series is a member of the fine, illitic, mesic family of Aeric Ochraqualfs consisting of deep somewhat poorly-drained soils on uplands. The soils commonly exhibit AASHTO classification values in the A-4 to A-7 range. The Mahoning series is considered to be a poor source material for road fill because of low strength. The Mahoning series is of large extent and is found in the Northeastern Ohio area. The type location of the Mahoning series is in Lorain County, Ohio. The soil sample used in the study was obtained near the type location. The AASHTO classification of the soil sample was A-7-6.

Because the Mahoning series represents the only illitic soil evaluated in the program, the effects of three sulfate wastes on the strength properties were determined. The sulfate wastes are: phosphogypsum (PG3), flue gas desulfurization solids (FG1), and neutralized acid mine drainage solids (AMD). The effect of lime/sulfate waste combinations on the strengths of the Mahoning series has also been evaluated. The inclusion of fly ash in PG3/lime mixtures has been studied, and cement kiln dust has been substituted for lime in the AMD systems. The unconfined compressive strengths as a function of time for the Mahoning/PG3 systems studied are plotted in Figure 24, the Mahoning/FG1 systems in Figure 25, and the Mahoning/AMD systems in Figure 26. The linear regression coefficients, standard deviations, and statistical significance of all of the Mahoning systems are presented in Table 32.

As can be seen from the figures and the table, the inclusion of sulfate waste has little effect on the strengths of Mahoning soil. Addition of FG1 to the soil tends to decrease strength, and the decrease appears to be significant at the 95% level in the regression analysis. Thus, we conclude that the incorporation of sulfate waste by itself into Mahoning soils (and perhaps illitic soils in general) is not desirable.

Strengths can be improved by using binary mixtures of lime-sulfate waste. The effect is particularly pronounced in the lime-PG3 system. In this case, there is a definite synergism between lime and sulfate waste that results in improved strength properties. The synergism also exists in the FG1/lime system, but not to the extent that it does in the PG3/lime system. Strength development in the lime/AMD system is less than that which can be achieved by lime alone. The lime/sulfate waste effects are due to sulfate content in the waste. The sulfate content of PG3 is about 40%, while the sulfate contents of FG1 and AMD are about 13% and 2%, respectively. In addition, the illite is an alumina-bearing mineral. Thus, the combination of lime, sulfate, and alumina would be expected to yield ettringite for soil stabilization. For the case of Mahoning and other illitic soils, strength development hinges upon the amount of sulfate available in the sulfate wastes.

Strengths of the PG1/lime system can be increased further by adding fly ash to the stabilization mixture. The addition of the fly appears to have little effect on the overall behavior of the lime and sulfate waste (regression coefficients do not change when fly ash is added). Thus, the positive effects of the fly ash are probably due to large quantities of alumina for ettringite formation.

The use of kiln dust in conjunction with the AMD sulfate waste results in improved strengths over those which are obtained with the AMD alone. However, the AMD/kiln dust mixture is not as effective as kiln dust alone. This behavior is believed due to the fact that the AMD waste contains iron oxide as a major constituent, along with relatively small amounts of sulfate. Iron oxide is less apt to form calcium sulfosalts than is alumina. Hence, the AMD waste should be expected to be less effective towards either lime or kiln dust with respect to strength development than are the phosphogypsums or flue gas desulfurization solids.

Curing time in Mahoning/FG1 and Mahoning/AMD systems tends to have a negative effect on strength, and this effect appears to have some statistical significance, the strength of untreated soil also seems to deteriorate slowly with time, and represents one of the few cases in which the deterioration may be significant. In all cases, the strength deterioration is slow and may represent an equilibration to a strength less than that obtained initially. In other words, the forcing of the data into a straight line format may lead to misleading results.

4. Memphis series - The Memphis series is a member of the fine-silty, mixed, thermic family of Typic Hapludalfs, and consists of well-drained, acid soils of uplands that have formed in silty materials. The soils vary in their AASHTO classification from A-4 in the A horizon to A-6 and A-7 in the B horizon. It is a fair source material for road fill but tends to have low strength. The Memphis series is found in Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee, and is of large extent. The type location for the Memphis series is in Warren County, Mississippi; the sample used for the study was obtained in West Feliciana Parish, Louisiana. The AASHTO classification for the Prentiss soil used in the study was A-7-C.

Strength properties of the Memphis series were determined using specimens containing two types of phosphogypsum--PG1 from Florida, and PG3 from Texas. The PG1 system was evaluated in combination with lime, whereas the PG3 system was evaluated as a single component. The unconfined compressive strength-time results for the Memphis/PG1 system are shown in Figure 27, and those for the Memphis/PG3 system in Figure 28. Linear regression analysis findings are presented in Table 33.

The response of the Memphis series to phosphogypsum and phosphogypsum-lime treatment follows predictable patterns. Phosphogypsum (PG3) by itself does nothing to improve the strength of Memphis soil. In fact, it may tend to degrade strengths. The PG3 regression coefficient is -0.99 in the Memphis/PG3 system, and is significant at the 99.9% level. The magnitude of the coefficient implies about a 1-psi decrease in strength for each percent of sulfate waste added. At low dosages of PG3, little effect would be noted.

On the other hand, lime tends to improve strength as expected. Substantial increases in strength can be achieved using lime-phosphogypsum mixtures, again as expected. Thus, one concludes that phosphogypsum alone would probably not be used for soil stabilization purposes; rather one would choose the combination of phosphogypsum with small quantities of lime added.

5. Miami series - The Miami series is a member of the fine-loamy, mixed, mesic family of Typic Hapludalfs. The series consists of deep, well-drained soils formed in loess and the underlying glacial till. The AASHTO classification of the Miami series ranges from A-4 to A-7. The soil is considered to be a fair source of material for road beds, but is susceptible to frost action and often exhibits low strengths. The soil is extensive and found in Indiana, Southern Michigan, Northeastern Illinois, Southwestern Wisconsin, and Western Ohio. The type location of the Miami series is in Rush County, Indiana. The experimental sample was collected in Boone County, Indiana and had an AASHTO classification of A-6.

Three sulfate wastes have been studied in conjunction with the Miami series: phosphogypsum from North Carolina (PG2), flue gas desulfurization solids from Illinois (FG1), and neutralized acid mine drainage waste (AMD). The studies involving PG2 and AMD dealt with the effects of these materials as single additives to the soil, while FG1 was used in conjunction with lime. Strength versus time plots for the PG1 and AMD systems are presented in Figure 29, and for the FG1/lime system in Figure 30. Results of linear regression reduction of unconfined compressive strength data are given in Table 34.

The use of sulfate waste alone does not affect strength to any great degree. The use of a high-sulfate content waste (PG3) may tend to be slightly deleterious, whereas the use of a low-sulfate content material (AMD) has virtually no effect on strength.

Strengths of the Miami series respond favorably to lime treatment and to lime/FG1 treatment. Unlike some other cases, the inclusion of the sulfate waste with lime does not improve strength properties over those obtained with lime alone. This phenomena may be due to the fact that the FG1 material contains insufficient sulfate for the formation of ettringite.

Based on the above observations, we conclude that stabilization of Miami and similar soils can be achieved with lime. If, however, there is a source of flue gas desulfurization waste nearby a particular site, this material could be utilized without harm. In this case, utilization would serve merely as a disposal mechanism since indications are that it would do little for improving strengths.

6. Sassafras series - The Sassafras series is a member of the fine-loamy, siliceous mesic family of Typic Hapludults, and consists of well-drained, moderately permeable soils on uplands of the mid-Atlantic coastal plain. The series is of large extent and found in Delaware, Maryland, New Jersey, Pennsylvania, and Virginia. The type location of the Sassafras soil series is in New Castle County, Delaware. The sample gathered for the experimental work was taken from Queen Annes County, Maryland. The AASHTO classification of the soil was A-6.

The effect of two low-sulfate content wastes on the strengths of the Sassafras soil have been evaluated. The wastes are flue gas desulfurization solids (FG1) and neutralized acid mine drainage solids (AMD). Both materials have been mixed with lime to determine effects of binary lime-sulfate waste mixtures. Unconfined compressive strengths as a function of time are plotted in Figure 31 for the Sassafras/FG1 system, and in Figure 32 for the Sassafras/AMD systems. Results of the linear regression data analysis are summarized in Table 35 for all systems studied using the Sassafras series.

These data shown in the figures and table follow what has now become a typical pattern. The sulfate wastes have virtually no effect on the strength development of soil. There is a definite improvement in strength properties when lime/sulfate waste mixtures are used. The combination of lime/FG1 yields better strengths than does lime/AMD, probably due to the greater sulfate content in the FG1. The lime/AMD system is really no better than the lime system, perhaps due to iron oxide being a significant constituent in the AMD waste.

As was observed in other siliceous soils, e.g., Exum, the Sassafras series responds favorably to lime-sulfate waste treatment. The conclusion that general soil minerology is insufficient to predict behavior towards lime/sulfate waste stabilization is thus reinforced.

7. Shelby series - The Shelby series is a member of the fine-loamy, mixed, mesic family of Typic Argiudolls. The series consists of moderately well-drained soils formed in clay loam glacial till under prairie grasses on uplands. The properties of the soil fall into the A-6 and A-7 categories in the AASHTO classification system. The soil is a poor source material for road fill because of its low strength. The Shelby series is of large extent and found in Southern Iowa, Northern Missouri, Eastern Nebraska, and Northeastern Kansas. The type location is in Adair County, Iowa, and the Shelby sample used for the laboratory studies was obtained at the type location. The AASHTO classification of the Shelby sample was A-7-6.

Flue gas desulfurization waste from Kansas (FG2) and acid mine drainage neutralization solids from Pennsylvania (AMD) were used as sulfate wastes in the experiments with the Shelby series. The effects of lime on the two soil/sulfate waste systems were also evaluated. In addition, cement kiln dust was investigated as a lime substitute in the FG2 systems. Plots of the Shelby/FG2 strengths are presented in Figure 33, and of the Shelby/AMD strengths in Figure 34. Linear regression analysis results are presented in Table 36.

The inclusion of both FG2 and AMD into Shelby soils appears to have a positive effect on unconfined compressive strength. The FG2 material tends to be more effective at low concentrations than at high concentrations as indicated by negative value of the sulfate waste coefficient.

Strengths of the Shelby soil do not seem to be affected by lime to any great extent. However, they do tend to respond positively to lime/FG2 mixtures, but not to lime/AMD mixtures. The response of lime/FG2 systems may be related to the presence of fly ash in the FG2 material (fly ash is collected along with desulfurization products in the scrubber); and lack of response of the AMD may be due to the quantities of iron oxide in the waste. It is unlikely that the differences are due to sulfate content, since both wastes contain about the same quantity of sulfate.

When kiln dust is mixed with the Shelby series, one notes a significant improvement in strength properties. An even greater effect is noted when kiln dust and FG2 are used in combination. These phenomena may be due in part to the combination of lime, sulfate, and clay in the kiln dust--a natural combination for promoting the function of ettringite. These ingredients combined with the sulfate and fly ash in FG2 would tend to enhance soil stabilization characteristics.

8. Tama series - The Tama series is a member of the fine-silty, mixed, mesic family of Typic Argiudolls, and consists of well-drained soils formed in loess under prairie vegetation on uplands. The AASHTO classifications of the Tama series fall into the A-6 to A-7 range. The soil is a poor material for road fill because of low strength and excess humus. The soil is extensive, large areas being found in Illinois and Iowa with smaller areas in Minnesota and Wisconsin. The type location is in Tama County, Iowa. The sample gathered for laboratory purposes was collected in Tama County, but not at the type location. The AASHTO classification of the Tama soil sample was A-7-6.

Three sulfate wastes were evaluated as single ingredients and in combination with lime. The sulfate wastes used are phosphogypsum (PG3), flue gas desulfurization waste (FG1), and acid mine drainage solids (AMD). The linear equations relating strength and time are plotted in Figure 35 (for Tama/PG3 systems), Figure 36 (for Tama/FG1 systems), and Figure 37 (for Tama/AMD systems). The regression coefficients, standard deviations, and statistical significances are shown in Table 37.

Strengths of the Tama series are relatively nonresponsive to additions of PG3, FG1, and AMD. They seem to be also nonsensitive to lime. When lime and low-sulfate content wastes (FG1 and AMD) are used together, the soil continues to be unresponsive. On the other hand, strengths are enhanced when lime/PG3 combinations are used. The lack of response to lime systems may be due in part to organic matter in the soil. While organic matter was not determined, its presence in the Tama series has been noted as important in the soil description. It has been well established elsewhere that soils with organic matter tend to be unresponsive to moderate dosages of lime.

When lime is mixed with a high-sulfate content waste, e.g., PG3, the data from this study suggest that some of the adverse effects of organic matter may be overcome. When lime is mixed with low-sulfate content materials, e.g., FG1 or AMD, there is insufficient sulfate to offset the negative effects of organic matter.

9. Wharton series - The Wharton series is a member of the clayey, mixed, mesic family of Aquic Hapludults, and consists of moderately well-drained soils on uplands formed in material weathered from shale and siltstone. The AASHTO classification of Wharton soils ranges from A-4 to A-7. It is a poor material for road fill because of its inherent low strength. The series is of large extent and occurs in Kentucky, Maryland, Ohio, Pennsylvania, West Virginia, and possibly Eastern Tennessee. The type location is in Indiana County, Pennsylvania, where the sample used for laboratory study was collected. Its AASHTO classification was A-7-6.

The Wharton soil was treated with flue gas desulfurization waste (FG1) and neutralized acid mine drainage sludge (AMD) to determine the response of soil strengths to sulfate waste and sulfate waste/lime additions. The AMD waste was also evaluated with respect to kiln dust as a lime substitute. The strengths of the Wharton/FG1 system are plotted in Figure 38, and those of the Wharton/AMD systems in Figure 39. Regression coefficients, etc., are shown in Table 38.

The Wharton soil does not appear to be responsive to either sulfate waste (AMD) or lime alone. The lack of response to lime is unexpected, since the soil is clayey. The addition of cement kiln dust is seen to have little effect as soil strength properties which was also not expected. The behavior towards lime and kiln dust may indicate that lime requirements for neutralization of clay particles are high, and that these requirements were not met by the amounts of lime or kiln dust used in the experiments.

Lime/sulfate waste mixtures, on the other hand, tend to improve strengths of the Wharton soil, particularly the lime-FG1 combination. The enhancement of strength with the FG1 material is likely due to the large content of sulfate in the waste. Similarly, strengths may be improved by using kiln dust-AMD combinations. However, the improvement is not substantial in this case.

The general lack of response of Wharton soils to sulfate waste, lime, and kiln dust treatment emphasizes the need to evaluate each situation before making a commitment towards soil stabilization involving sulfate waste. The Wharton case indicates that soils expected to respond positively to treatment may not actually do so. Perhaps, if the minimum lime requirements are established for such soils, proper estimates of lime/sulfate waste ratios could be ascertained.

C. Class III Soils: Plasticity Index > 25, Nonmontmorillonitic

The discussion in this section for Class III soils follows the same format used for the Classes I and II soils immediately preceding. The effect of sulfate waste addition to each soil is discussed, together with plots of unconfined compressive strength against time. The plots are derived from the linear equations developed by the regression analysis of unconfined compressive strength data, and show the strength-time relationships for untreated soil, soil treated with 6% sulfate waste, and soil treated with 2% other additives, i.e., lime, cement kiln dust, or fly ash. The general caveat pertaining to time stated with regard to the Class I soils is applicable here: one should not extrapolate strength development past 28 days because of the assumption that strength development is linear with curing time.

The Class III soils and associated sulfate wastes studied during the program are:

1. Chobee Series

   Lime
   PG1
   PG1/Lime

2. Craven Series

   Lime
   PG2
   PG1/Lime
   PG2/Lime/Fly Ash

3. Hartwell Series

   FG2

4. Higginsville Series

   Lime
   Kiln Dust
   FG1/Lime
   FG2
   FG2/Lime
   FG2/Kiln Dust

5. Katy Series

   Lime
   PG3
   PG3/Lime
   PG3/Lime/Fly Ash

6. Upshur Series

   Lime
   FG1/Lime
   AMD

1. Chobee series - The Chobee series is a member of the fine-loamy, mixed, noncalcareous, hyperthermic family of Typic Argsaquolls, and consists of very poorly-drained soils with a very shallow water table. The topsoil of the Chobee Series is a sandy loam having an AASHTO classification of A-2-4. The B horizon, beginning about 7 in. below the surface and the source of the experimental sample, is a sandy clay loam falling in the A-6 and A-7 AASHTO categories. The soil is a fair material for road fill, but the high water table (within 10 in. of the surface) presents problems for this application. The soil is of moderate extent and occurs in Central Florida. The type location is in Okeechobee County, Florida. The sample used for study was collected near the type location site and had an AASHTO classification of A-7-6.

The Chobee series was evaluated with respect to Florida phosphogypsum, PG1, and FG1/lime mixtures. Unconfined compressive strength versus time linear equations have been plotted in Figure 40, and pertinent results of the linear regression analysis of strength data presented in Table 39.

The effect of PG1 addition on unconfined compressive strength does not appear to be of real importance. When lime is added to the PG1, an increase in strength is observed. However, strengths of PG1-lime mixtures are about the same as those of lime alone. Thus, Chobee represents a soil which can be stabilized with lime. Waste sulfate can also probably be included with the lime with no adverse effect. However, the use of waste sulfate in this application would serve primarily as disposal rather than utilization since no benefits in strength are derived from its usage.

2. Craven series - The Craven series is a member of the clayey, mixed, thermic family of Aquic Hapludults, and consists of moderately well-drained soils on coastal plain uplands. The surface horizon is relatively coarse, having an AASHTO classification of A-4. The lower horizons are more fine-grained and are in the A-6 and A-7 AASHTO categories. The sample was taken from the lower horizons. The series is of large extent and found in the coastal plains of Georgia, North Carolina, South Carolina, and Virginia, and perhaps in other southern states. The type location and site of sample acquisition is in Craven County, North Carolina. The AASHTO classification of the Craven sample was A-7-6.

The Craven series was used as one of the soils in which the sulfate waste in combination with lime and fly ash was evaluated. The sulfate waste studied was the North Carolina phosphogypsum, PG2. Plots of the strength-time relationships for the Craven/PG2 systems are shown in Figure 41, and the linear regression coefficients, etc., in Table 40.

Adding phosphogypsum to the Craven soil has little effect on strength at the 6% level. There may be small increases in strength at lower levels of addition, since the sulfate waste regression is negative and is significant in the statistical sense. If lime is added to the soil, very definite improvement in strength is noted.

As has been observed with many lime/phosphogypsum mixtures, the usage of the two materials in combination will greatly benefit strength development. The Craven series follows this trend very nicely. The ternary combination of lime, phosphogypsum, and fly ash is also extremely beneficial for enhancing strength development, particularly within the few few days of cure.

3. Hartwell series - The Hartwell series is a member of the fine, mixed, thermic family of Typic Argialbolls. The series consists of deep, somewhat poorly-drained soils formed in loess that contains a component residuum from shales on uplands. The AASHTO characteristics of the Hartwell soil range from A-4 to A-6 in the top horizon to A-7 in the B horizon. It is a poor source material for road fill because of low strength and adverse shrink-swell properties. The series is extensive and found throughout Southwestern Missouri and perhaps Eastern Kansas and Northeastern Oklahoma. The type location is in Henry County, Missouri. The sample collected for the experimental work was also obtained in Henry County, but not at the type location. The AASHTO classification was A-7-6.

Flue gas desulfurization waste from Kansas (FG2) was tested as a soil stabilizer. The plot of strengths generated by adding 6% FG2 to Hartwell soil as a function of time is shown in Figure 42. Pertinent results of the linear regression analysis of strength data are presented in Table 41.

The three regression coefficients--moisture, time, and FG2 addition--for the Hartwell/FG2 system are significant at the 99.9% level. However, the magnitude of the coefficients is small, hence, effects are small. Thus, we conclude that FG2 could be disposed of in Hartwell soil, but such disposal would yield no real benefits with regard to strength.

4. Higginsville series - The Higginsville series is a member of the fine-silty, mixed, mesic family of Aquic Argiudolls, and consists of deep, somewhat poorly-drained, slowly permeable soils. The AASHTO classification of the subsoils comprising this Higginsville series is A-7-6. The soils are poor source materials for road fill because of high shrink-swell characteristics. The series is thought to be of large extent and occurs in west central Missouri. The type location is in

Lafayette County, Missouri. The sample used for evaluation/testing was obtained near the type location and had an AASHTO classification of A-7-6.

The Higginsville series was evaluated in conjunction with the two flue gas desulfurization wastes, FG1 and FG2. In addition, combinations of the two wastes with lime were evaluated, and kiln dust was substituted for lime with FG2. Strength versus time plots for the Higginsville/FG1 systems are shown in Figure 43, and for the Higginsville/FG2 systems in Figure 44. Linear regression coefficients along with standard deviations and statistical significance are given in Table 42.

Strengths of the Higginsville soil are not improved by lime addition at the 2% level. Addition of 6% FG2 may yield some improved strength. The combinations of lime and FG1 or FG2 do not result in improved strength. In fact, the lime/FG2 combination is not as good as the FG2 by itself. The results of the data analysis in Table 42 indicate that the regression coefficients are not significant and hence differences in strength among the various systems are likely due to experimental error.

In the case of the FG2-kiln dust studies, the kiln dust coefficients are significant at the 99.9% level. The addition of 2% kiln dust to the Higginsville soil does not improve strength properties. Because the regression coefficient is negative, an increased addition would tend to degrade properties. When, however, the kiln dust is mixed with FG2, a very definite increase in strength is observed.

5. Katy series - The Katy series is a member of the fine-loamy, siliceous, thermic family of Aquic Paleudalfs, and consists of very poorly drained, very slowly permeable upland soils. The estimated soil properties of the Katy series range from A-4 to A-7 in the AASHTO classification scheme. The soil is a poor source of road fill material because of its low strength. The Katy series is found in the eastern part of the coastal prairie in Texas and is extensive. The type location is in Fort Bend County, Texas, and the sample collected for laboratory study was taken nearby. The AASHTO classification of the experimental soil sample was A-7-6.

The effect of phosphogypsum (PG3) on the strength of the Katy soil has been evaluated. Combinations of PG3 and lime, and PG3, lime, and fly ash were also studied. The strength versus time plots are presented in Figure 45, and results of the strength data analysis in Table 43.

The results of the Katy series studies follow those of other siliceous soil series. The sulfate waste has little or no effect, although there appears to be a tendency towards decreasing strength by phosphogypsum addition. Any adverse effects arising from the phosphogypsum can be overcome, however, by the addition of lime. Lime/phosphogypsum mixtures will tend to achieve strengths greater than those with lime alone over long time periods. Finally, strengths can be increased substantially by using a ternary mixture of phosphogypsum, lime, and fly ash.

The Katy soil seems to behave like a classical siliceous soil. It is relatively unresponsive to lime stabilization. It does appear to have some alumina available for ettringite formation as indicated by the slow increase in strength with time. When additional alumina is made available in the form of fly ash, strengths increase rather markedly in the presence of lime and phosphogypsum.

6. Upshur series - The Upshur series is a member of the fine, mixed, mesic family of Typic Hapludalfs. It consists of deep, well-drained soils on uplands and was formed in material weathered from shale or siltstone. The AASHTO classification of the soil ranges from A-6 to A-7. It is a poor material for road fill because of its high shrink-swell potential. The Upshur series of of moderate extent and occurs in Western West Virginia, Southwestern Virginia, Southwestern Pennsylvania, Southeastern Ohio, Eastern Tennessee, and Northeastern Kentucky. The sample used for the testing program was collected near the type location in Wood County, West Virginia, and had an AASHTO classification of A-7-6.

Flue gas desulfurization solids (FG1) and neutralized acid mine drainage waste (AMD) were used as candidate soil stabilizers for the Upshur series. The linear regression results of unconfined compressive strength data with time have been plotted for the FG1 systems in Figure 46 and for the AMD system in Figure 47. The results of the linear regression analysis itself are in Table 44.

Strengths of Upshur soils do not appear to be influenced by either sulfate waste treatment or lime/sulfate waste treatment. The Upshur series was not studied in as great a depth as some of the other soils, so a firm interpretation of the data is not practical. However, the data do follow the general trend established in the Hartwell and Higginsville series that inclusion of a low sulfate content material and lime does not greatly affect unconfined compressive strength of Class III soils.

D. Class IV Soils: Plasticity Index > 20, Montmorillonitic

The fourth and last class of soils investigated during the project were fine-grained montmorillonitic soils. One soil--Fellowship series--is coarser than the other montmorillonitic soils and its plasticity index falls in the 20 to 25 range. Another soil--Sharpsburg series--has been evaluated with five of the six sulfate wastes considered in the study to detect differences among sulfate wastes of the same type, e.g., phosphogypsum or flue gas desulfurization solids. Each soil is discussed with respect to its strength properties as affected by sulfate waste treatment and sulfate waste-additive treatment. The discussion again revolves around the results of the linear regression analysis of unconfined compressive strength data.

The five soils falling into the Class IV category are:

1. Fellowship

   Lime
   Cement
   PG1
   PG1/Lime
   PG1/Lime/Fly Ash
   PG1/Cement

2. Lake Charles Series

   PG3

3. Sharkey Series

   Lime
   PG1/Lime
   PG3
   PG3/Lime

4. Sharpsburg Series

   Lime
   Kiln Dust
   PG2
   PG2/Lime
   PG2/Lime/Fly Ash
   PG3
   PG3/Lime

FG1/Lime
FG2
FG2/Lime
FG2/Kiln Dust
AMD
AMD/Lime

5. Summit Series

Lime
Kiln Dust
FG2
FG2/Lime
FG2/Kiln Dust

1. Fellowship series - The Fellowship series is a member of the fine, montmorillonitic, hyperthermic family of Typic Umbraqualfs, and consists of poorly-drained, very slowly permeable soils formed in thick beds of clayey marine sediment. The soils are located in the Florida peninsula and are of moderate extent. The type location is in Marion County, Florida. The sample acquired for experimental testing was collected near the type location and had an AASHTO classification of A-7-6.

The Fellowship series was evaluated with respect to the Florida phosphogypsum PG1. The soil was also chosen as one to be evaluated with lime/PG1, and lime/PG1/fly ash mixtures. Because the Fellowship series is more course-grained than other montmorillonitic soils, a few specimens including portland cement and cement/FG1 stabilization were also undertaken. The Fellowship/PG1/lime system strength versus time plots are presented in Figure 48, and those of the Fellowship/PG1/cement system in Figure 49. The pertinent results of the linear regression analysis for unconfined compressive strength data are given in Table 45.

The strengths of the Fellowship series seem to be relatively unresponsive to phosphogypsum and phosphogypsum-additive treatment. The addition of PG1 at the 6% level appears to increase strengths by almost 50% during the initial curing period. However, the regression coefficients are insignificant in the statistical sense because of the wide variation in the data. Thus, one is forced to conclude that phosphogypsum effects on strengths are probably not real.

Addition of lime at the 2% level does not increase strengths appreciably. In fact, the negative regression coefficient for lime (significant at the 99% level) suggests that addition of larger amounts of lime would decrease strength. As will be seen in subsequent discussions of other montmorillonitic soils, the lime regression coefficient is consistently negative. The inclusion of sulfate waste with the lime does not greatly affect the unconfined compressive strength of the soil.

The negative effect of lime indicates that insufficient lime was used in the experiments to produce stabilization, and that extrapolation of data beyond 6% lime addition is unwarranted. Montmorillonitic soils are known to require high dosages to achieve strength improvement. Unlike nonmontmorillonitic soils, the evidence of the present study does not suggest that addition of sulfate waste decreases lime-dependence for stabilization of montmorillonitic soils.

When fly ash is added to the lime/phosphogypsum mixture, the resulting strengths still remain unchanged. This observation is contrary to what has been observed with the Classes I, II, and III soils, but is consistent with results from another montmorillonitic soil--Sharpsburg. Thus, we conclude that fly ash addition to lime/sulfate waste will not have any great benefit towards stabilizing montmorillonitic soils.

As mentioned earlier, the Fellowship series is coarser than other montmorillonitic soils; hence we undertook a limited number of tests on Fellowship/cement and Fellowship/PG1/cement specimens. The data for these tests are widely scattered and no definitive conclusions can be drawn. It does appear, however, that Portland cement/phosphogypsum addition follows the same general pattern as that observed with lime, i.e., the soil strengths are not particularly affected by cement-phosphogypsum stabilization.

2. Lake Charles series - The Lake Charles series is a member of the fine, montmorillonitic, thermic family of Typic Pelluderts. The Lake Charles clay is a somewhat poorly-drained, very slowly permeable upland soil, and has properties falling in the A-7 category of the AASHTO classification scheme. It is a poor material for road fill because of low strength and shrink-swell tendencies. The series is extensive (about 1 million acres) and is found in the Gulf Coast Prairies of Texas. The sample used for experimental work was acquired near the type location in Fort Bend County, Texas. The AASHTO classification of the soil sample was A-7-6.

The effect of phosphogypsum (PG3) addition on the unconfined compressive strength of Lake Charles soil was evaluated. The plot of unconfined compressive strength (6% level) against curing time is shown in Figure 50, and the results of the regression analysis for strength data given in Table 46.

The addition of phosphogypsum to the Lake Charles series has virtually no effect on the strength properties. This observation is consistent with others for montmorillonitic soils.

3. Sharkey series - The Sharkey series is a member of the very fine, montmorillonitic, nonacid, thermic family of Vertic Haplaquepts, and consists of poorly-drained, very slowly permeable soils. The AASHTO property classifications for the series fall into the A-6 and A-7-6 categories. The Sharkey soils are poor source material for road fill because they are too clayey, wet, and have the potential for shrink-swell. The series is extensive and occurs in the Mississippi River flood plain in Arkansas, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee. The type location is in West Feliciana Parish, Louisiana. However, the experimental sample used during the study was collected in St. John the Baptist Parish, Louisiana. Its AASHTO classification was A-7-5.

Strengths of the Sharkey series were evaluated with respect to two phosphogypsums--PG1 from Florida and PG3 from Texas. Lime/phosphogypsum mixtures were also evaluated. The strength versus time plots for Sharkey/PG1 are presented in Figure 51 and Sharkey/PG3 in Figure 52. Linear correlation coefficients, etc., are given in Table 47.

Addition of phosphogypsum to Sharkey soil does not affect unconfined compressive strength. Our results indicate that addition of lime to Sharkey soil has a negative effect, i.e., strengths decrease with increasing lime addition. Combinations of lime and phosphogypsum also do not affect strength properties.

4. Sharpsburg series - The Sharpsburg series is a member of the fine, montmorillonitic, mesic family of Typic Argiudolls, and consists of moderately well-drained soils formed in loess under prairie vegetation on upland divides and stream benches. The soil properties in the AASHTO classification are in the A-6 and A-7 range. It is a poor material for road fill because of its potential for shrink-swell and low strength. The Sharpsburg series is extensive and is located in Southeastern Iowa, Northwestern Missouri, Northeastern Kansas, and Southeastern Nebraska. The soil sample used for the experimental work was collected near the type location in Taylor County, Iowa and had an AASHTO classification of A-7-6.

The Sharpsburg series has been the most closely studied soil during the program. Five sulfate wastes were used: North Carolina phosphogypsum (PG2), Texas phosphogypsum (PG3), Illinois flue gas desulfurization solids (FG1), Kansas flue gas desulfurization solids (FG2), and Pennsylvania acid mine drainage neutralization waste (AMD). Each of the sulfate wastes was also evaluated with respect to lime addition. In addition, the ternary combination of lime/PG2/fly ash was studied, as was the binary combination of kiln dust/FG2. The unconfined compressive strength-time equations from the regression analysis have been plotted: Sharpsburg/PG2 in Figure 53, Sharpsburg/PG3 in Figure 54, Sharpsburg/FG1 in Figure 55, Sharpsburg/FG2 in Figure 56, and Sharpsburg/AMD in Figure 57. The linear regression coefficients, standard deviations, and statistical significance are summarized in Table 48.

The Sharpsburg results are typical of those obtained for the montmorillonitic soils. The addition of sulfate waste or lime has no major effect on soil strengths. The regression coefficient for the lime is negative as observed in the Fellowship and Sharkey series. However, the coefficient is smaller and it is statistically not significant. The combination of lime and phosphogypsum does not increase strengths as much as has been noted in the Class III fine-grained nonmontmorillonitic soils. However, the combination of lime/phosphogypsum will yield products having more strength than those obtained with the combination of lime/flue gas desulfurization waste or lime/neutralized acid mine drainage waste. These observations suggest that sulfate content waste is important in achieving the little stabilization obtainable using lime/sulfate waste, even in montmorillonitic soils.

The addition of fly ash to lime and phosphogypsum mixtures indicates that fly ash does not tend to make montmorillonitic soils strengths responsive to lime/sulfate waste treatment.

The cement kiln dust experiments with FG2 yield strengths which are better than those obtained with lime/FG2 treatment. Kiln dust alone seems to be a better stabilizer than does either lime or lime/FG2. However, kiln dust/FG2 mixtures yield strengths no better than those of kiln dust alone.

The variety of sulfate wastes used with Sharpsburg indicates that sulfate waste of the same type but from different sources will likely behave the same. We can detect no substantial differences between effects of two phosphogypsums used or between the two flue gas desulfurization wastes used. The lack of differences among the sulfate wastes of the same type has been consistently observed in all soils evaluated.

Effects which are noted, while being much smaller for the Sharpsburg series compared to nonmontmorillonitic soils, can be explained by variations in the sulfate content of the waste and to soil minerology. Thus we conclude that the proper utilization of sulfate waste hinges upon sulfate waste type more so than on specific sulfate waste source.

5. Summit series - The Summit series is a member of the fine, montmorillonitic, thermic family of Vertic Argiudolls. The series consists of moderatelywell-drained slowly permeable soils on uplands. The AASHTO properties of the Summit series are classified A-6 and A-7. The soil is a poor material for road fill because of low strength and shrink-swell properties. The series is extensive and located in Northwestern Arkansas, Southeastern Kansas, Southwestern Missouri, and Eastern Oklahoma. The type location is in Rogers County, Oklahoma, but the sample collected for testing was obtained in Woodson County, Kansas. The AASHTO classification of the Summit series sample was A-7-5.

Flue gas desulfurization solids from Kansas (FG2) were evaluated as a stabilization agent for Summit soil. Lime and cement kiln dust were also evaluated in conjunction with the FG2. The strength versus time plots are presented in Figure 58, and the pertinent results of the strength data analysis in Table 49.

The strengths generated by the Summit series treated in the several ways are similar to the corresponding results involving Sharpsburg. Kiln dust and kiln dust/FG2 are the only treatments which tend to enhance strengths of this montmorillonitic soil. Other treatments, including lime, do not appear to promote strength development in the Summit series.

V. CONCLUSIONS

The principal conclusions drawn from the study can be related to three kinds of treatment: sulfate waste, sulfate waste/lime, and sulfate waste/lime substitute. Individual conclusions within each of these three areas are presented below.

* Sulfate Waste-Treatment

1. Sulfate waste per se has little effect in promoting strength development in soils. On the other hand, the use of sulfate waste does not degrade soil strengths. Thus, sulfate waste can be mixed with soils as means of disposal. Coarse-grained soils are more likely to be chosen for sulfate waste disposal than are fine-grained soils.

2. Sulfate waste has virtually no effect on freeze-thaw characteristics of soils. Soils susceptible to deformation with freeze-thaw will also be susceptible when mixed with sulfate waste.

3. Sulfate waste addition will have an adverse effect on volume stability with some soils. Shrink-swell potential for soils sensitive to sulfate will be exacerbated when sulfate waste is incorporated into the soil. On the other hand, if shrink-swell potential is not related to sulfate sensitivity, sulfate waste can be mixed with soils without adversely affecting volume stability.

* Sulfate Waste/Lime-Treatment

1. The combination of lime and sulfate waste is an excellent material for promoting strength development in soils. The sulfate waste/lime mixture will react with the natural alumina in soil materials to produce ettringite, a calcium sulfoaluminate, which tends to increase unconfined compressive strength.

2. The sulfate content in the waste is important in reactions with lime. Relatively pure sulfate wastes, e.g., phosphogypsum with about 40% sulfate, will yield stronger products with soil/lime than do the more impure wastes, e.g., flue gas desulfurization solids having 15% sulfate.

3. The use of sulfate waste in conjunction with lime often reduces lime requirements for stabilization. When lime is mixed with sulfate waste, greater strengths can be achieved than can be obtained with the same quantity of lime. The rate of strength increase in the sulfate waste/lime soil systems is somewhat faster than that of comparable lime treated soils in most cases.

4. Lime in excess of that needed to satisfy the soil cation exchange capacity (CEC) is required for lime/sulfate waste stabilization. Initially, lime is adsorbed by clay particles. Following adsorption, the lime is available for strength development. If insufficient lime is added to exceed the soil CEC, the lime/sulfate waste mixtures tend to be ineffective towards strength development.

5. Coarse-grained soils are more amenable to lime/sulfate waste stabilization than are fine-grained soils treated at the same level. Fine-grained soils require a higher ratio of lime to sulfate waste, since more lime is adsorbed on the fine-grained particles and unavailable for reaction with sulfate.

6. Addition of fly ash to lime/sulfate waste mixtures will benefit strength development in soils. Fly ash is a secondary source of alumina when mixed with soils. Lime/sulfate waste will react with alumina in fly ash to form ettringite. The use of fly ash in siliceous soils appears to be quite beneficial towards strength development.

* Sulfate Waste/Lime Substitute-Treatment

1. The use of sulfate waste in conjunction with portland cement stabilization of soils is not as effective as that achieved with lime/sulfate waste combinations. Portland cement is sufficiently dissimilar from lime (probably due to its silica content) that its effects on soil strengths overshadow those of the lime/sulfate waste effects. In most cases, sulfate waste could be added to soil/cement systems without adverse effects. However, this application would be viewed as a means of sulfate waste disposal rather than a means of putting sulfate waste to use in a beneficial manner.

2. Cement kiln dust is an excellent soil stabilizer in its own right. Cement kiln dust, a by-product of portland cement manufacturing, is a mixture of calcined lime along with finely divided unburned limestone and clay raw feed. It also contains small amounts of sulfate ($\sim$ 5%) arising from combustion of fuel for the cement manufacturing process. The combination of lime, clay, and sulfate promotes the formation of ettringite when the dust is mixed with soils, and hence, it behaves much like lime/sulfate waste mixtures in this respect.

3. Cement kiln dust is also an excellent substitute for lime. The kiln dust normally contains about 50% free lime. When the dust is mixed with sulfate waste, the effect on soil strengths is similar to that observed in lime/sulfate waste treatment. In many cases, strengths greater than those achieved with lime/sulfate waste can be obtained with kiln dust/sulfate waste treatment, presumably because of the sulfate content of the kiln dust.

VI. RECOMMENDATIONS

The use of waste sulfate for remedial treatment of soils has been defined by the laboratory evaluations discussed in this report. It has been established that sulfate waste can be used to promote strength development in conjunction with lime or cement kiln dust stabilization. On the other hand, sulfate waste can be disposed of by mixing with soils without adverse effect on soil strengths. Therefore, it is recommended that two field studies be undertaken to demonstrate the principles uncovered by the laboratory work.

The first study should involve stabilization with lime/sulfate waste mixtures. Several sites should be used for the field tests which would involve a variety of soil textures and sulfate wastes. The most promising sulfate wastes for the field test are phosphogypsum and flue gas desulfurization sludges. Solids obtained from neutralized acid mine drainages or spent pickle liquor are insufficiently characterized to warrant their inclusion in the field test.

The second project should be concerned with the disposal of sulfate waste in road bases. In this case, it is recommended that the study be restricted to coarse- or medium-grained soils. While the laboratory studies indicated no major adverse effects on soil properties, it is believed that the coarse soils are more amenable towards sulfate waste disposal in this manner than are the fine-grained soils. This project should involve several sites so that the various sulfate wastes input can be considered. All of the sulfate wastes used in the laboratory study, including neutralized acid mine drainage solids, are considered as candidates for disposal in road base.

FIGURES

Figure 1 - Sources of Waste Sulfate

Figure 2 - Approximate Locations of Soil Series Selected for Experimental Evaluation With Sulfate Wastes

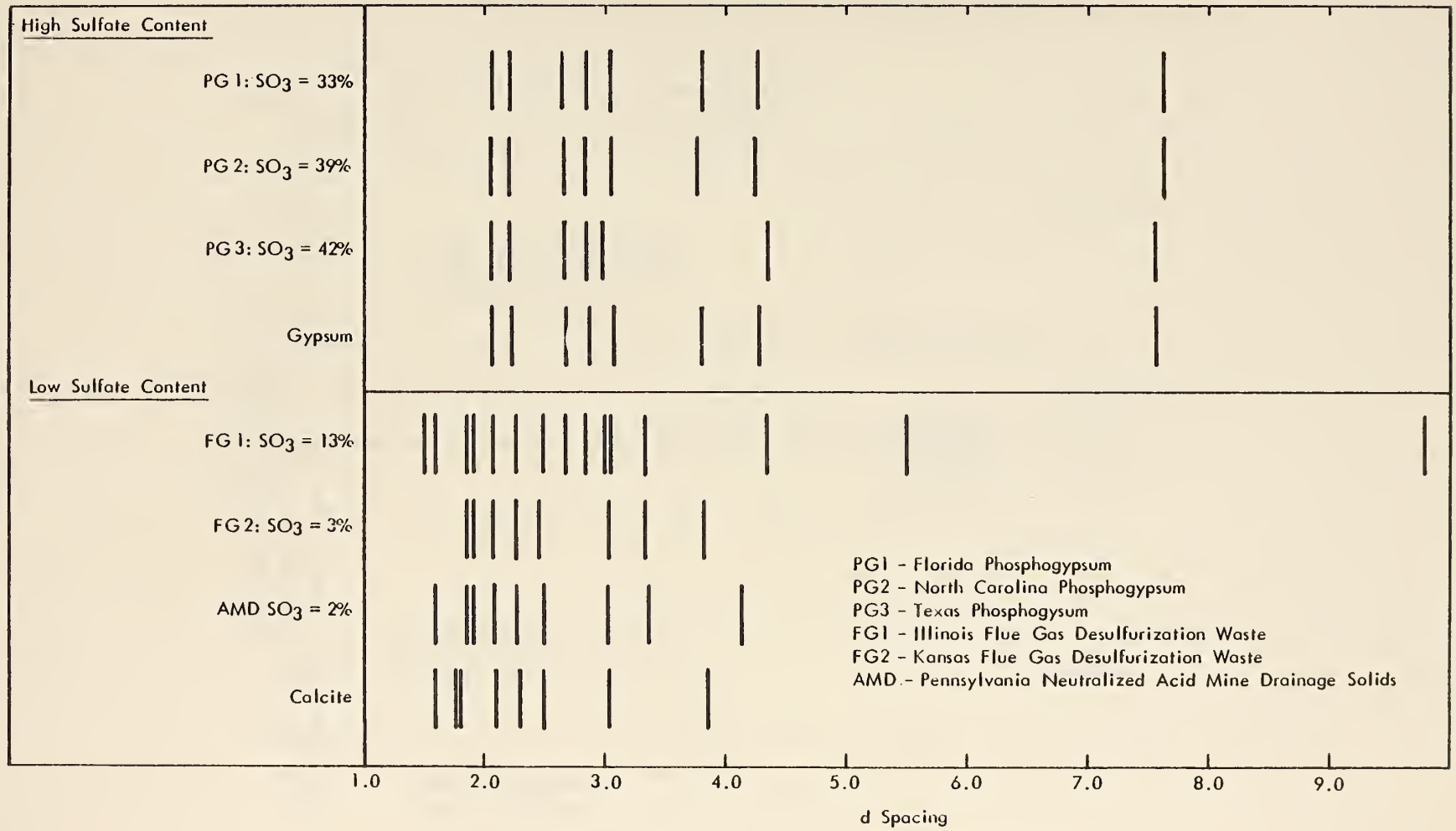

Figure 3. X-ray powder patterns of sulfate wastes.

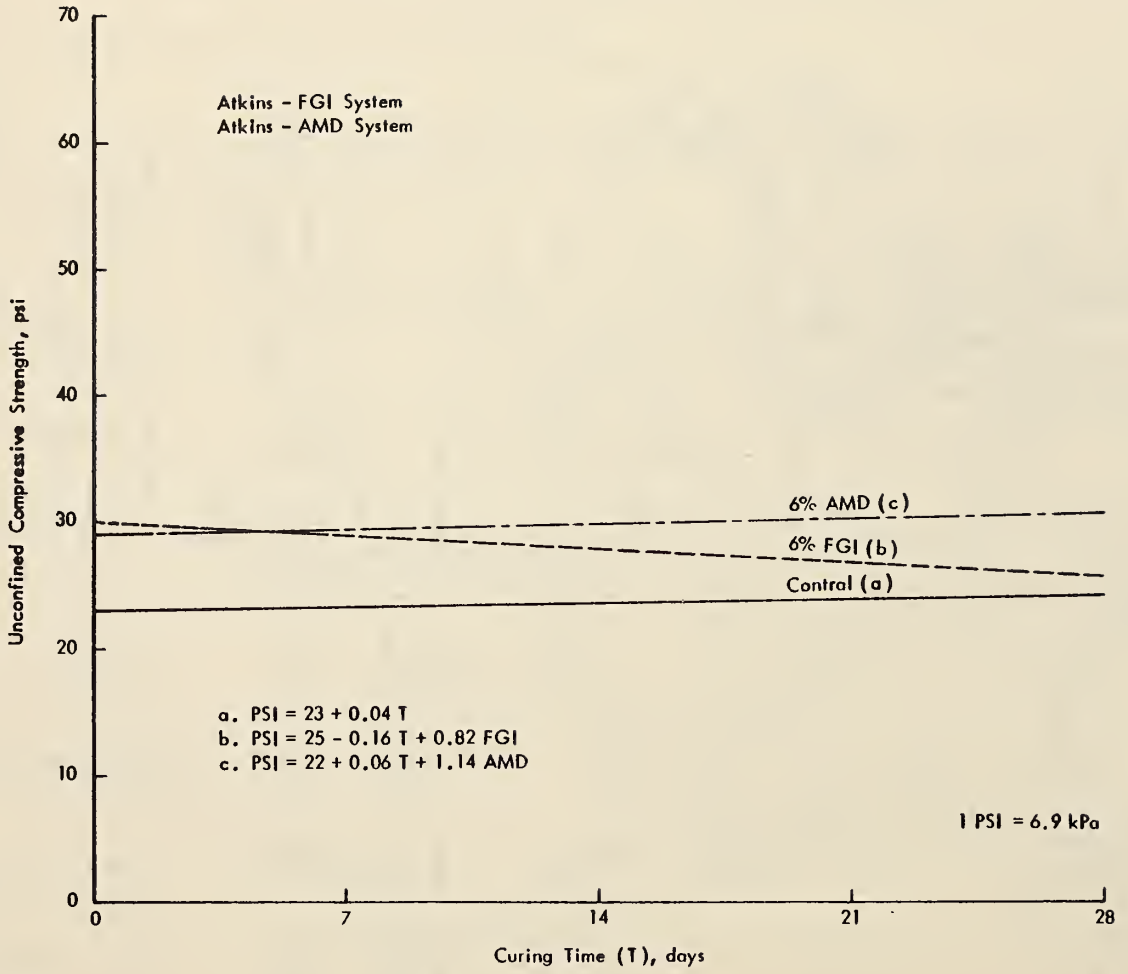

Figure 4. Linear regression plots of unconfined compressive strength versus curing time: Atkins/FG1 and Atkins/AMD systems.

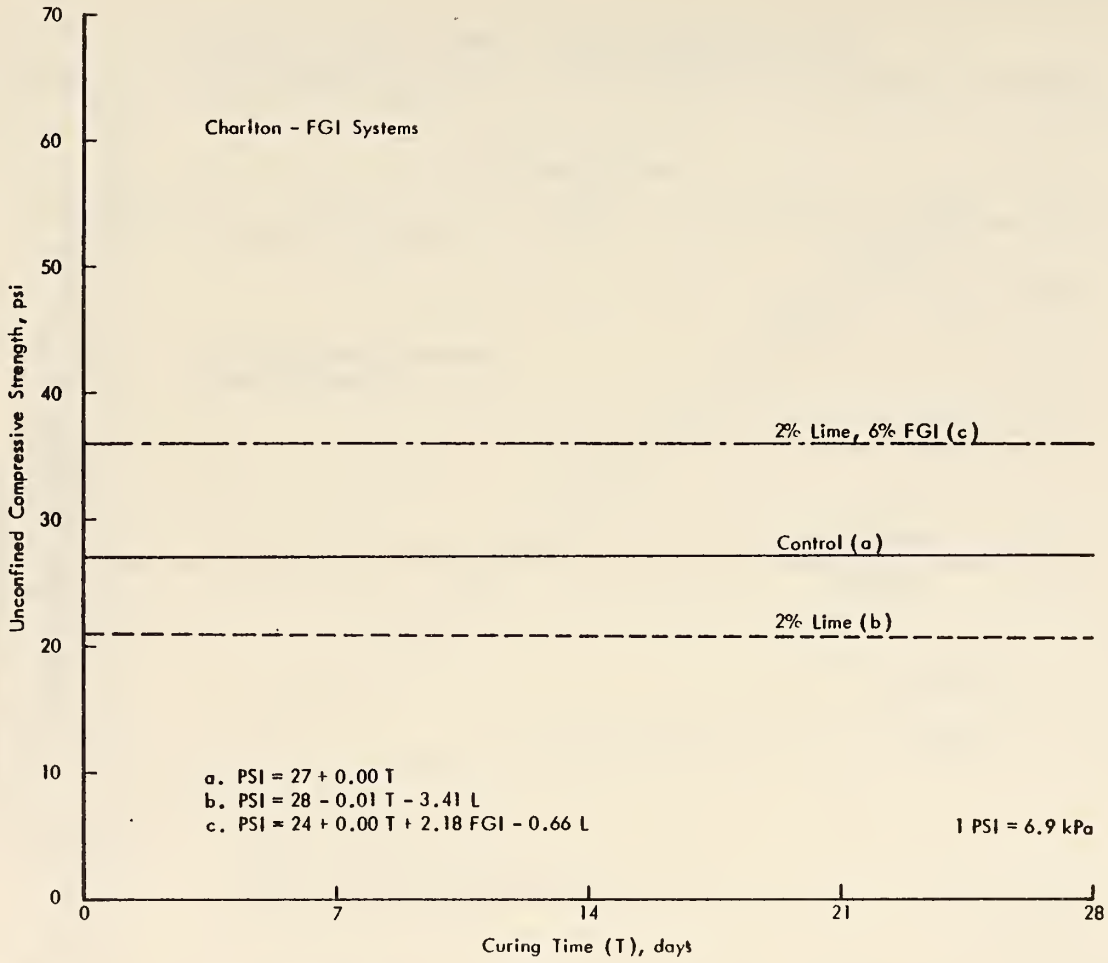

Figure 5. Linear regression plots of unconfined compressive strength versus curing time: Charlton/FGl systems.

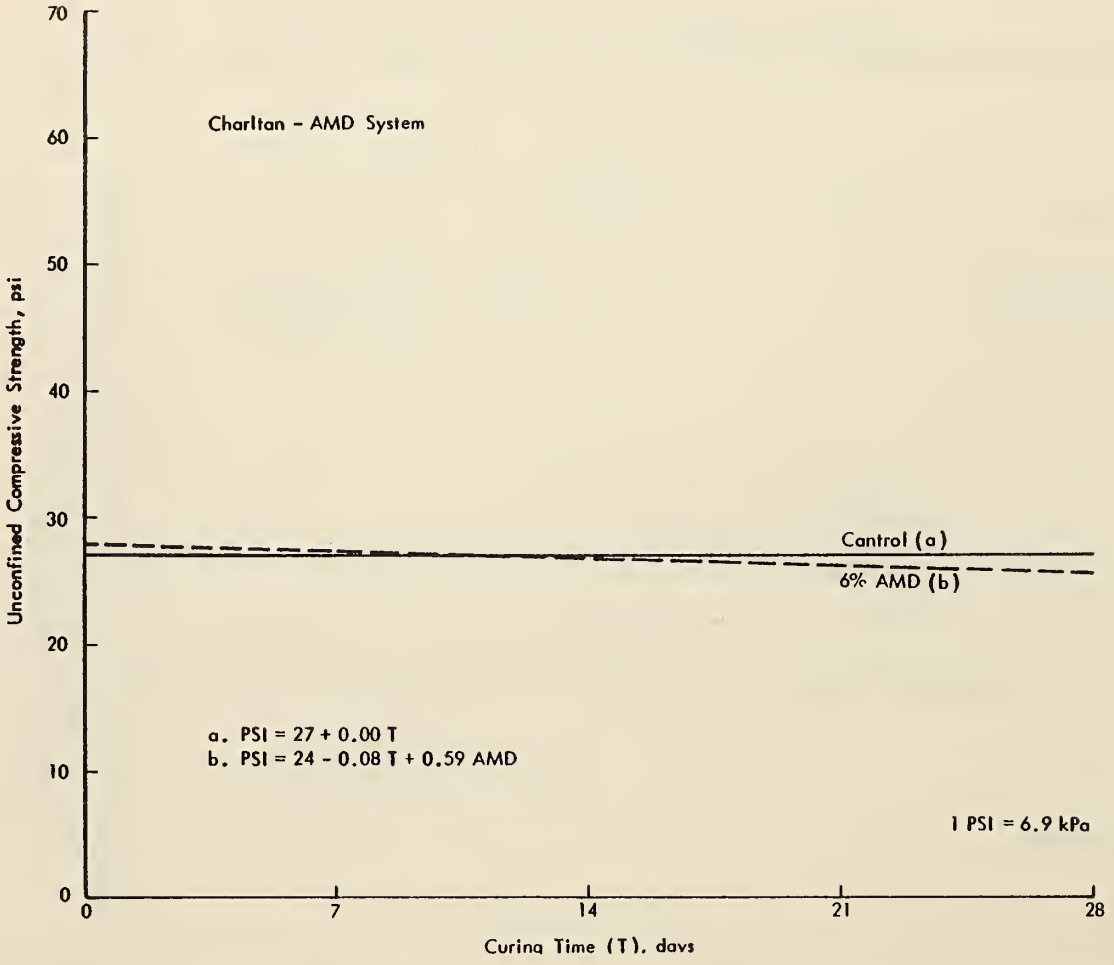

Figure 6. Linear regression plots of unconfined compressive strength versus curing time: Charlton/AMD system.

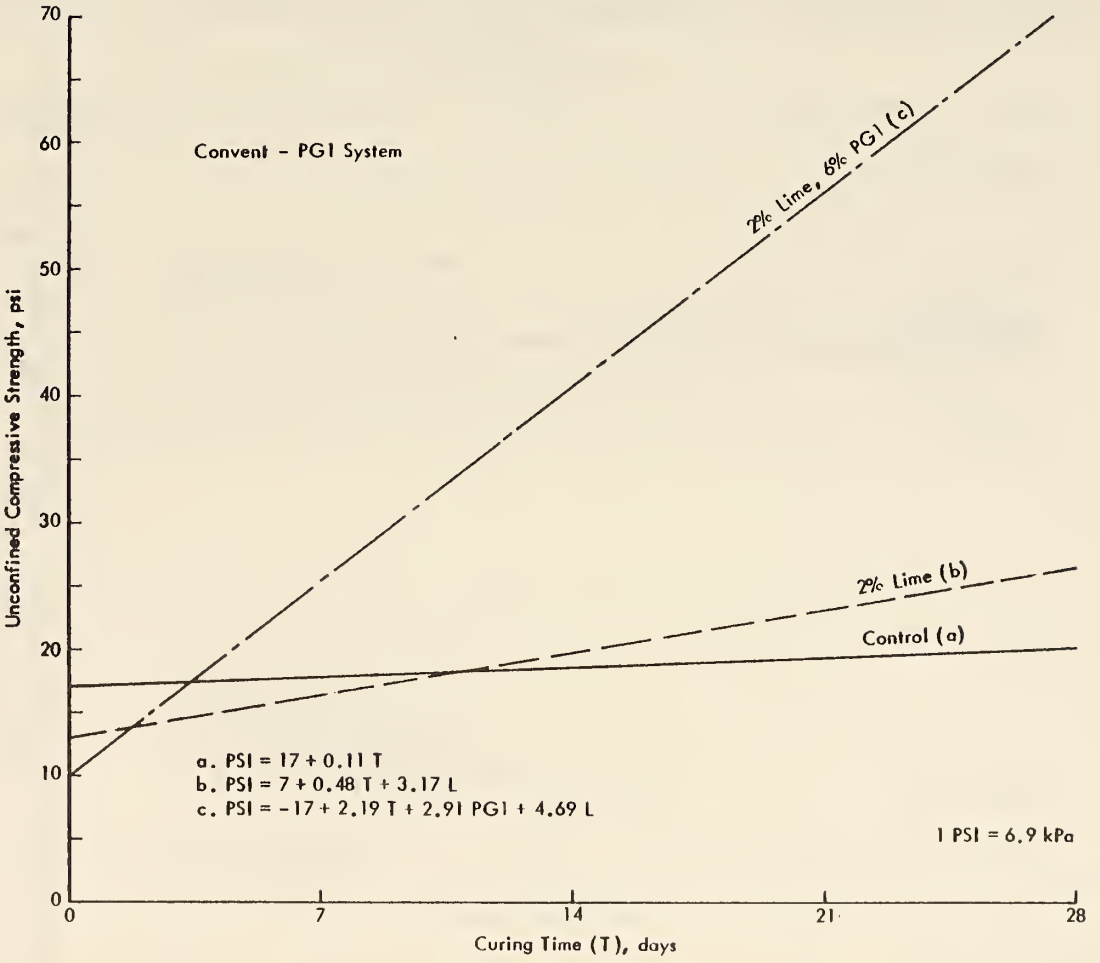

Figure 7. Linear regression plots of unconfined compressive strength versus curing time: Convent/PG1 system.

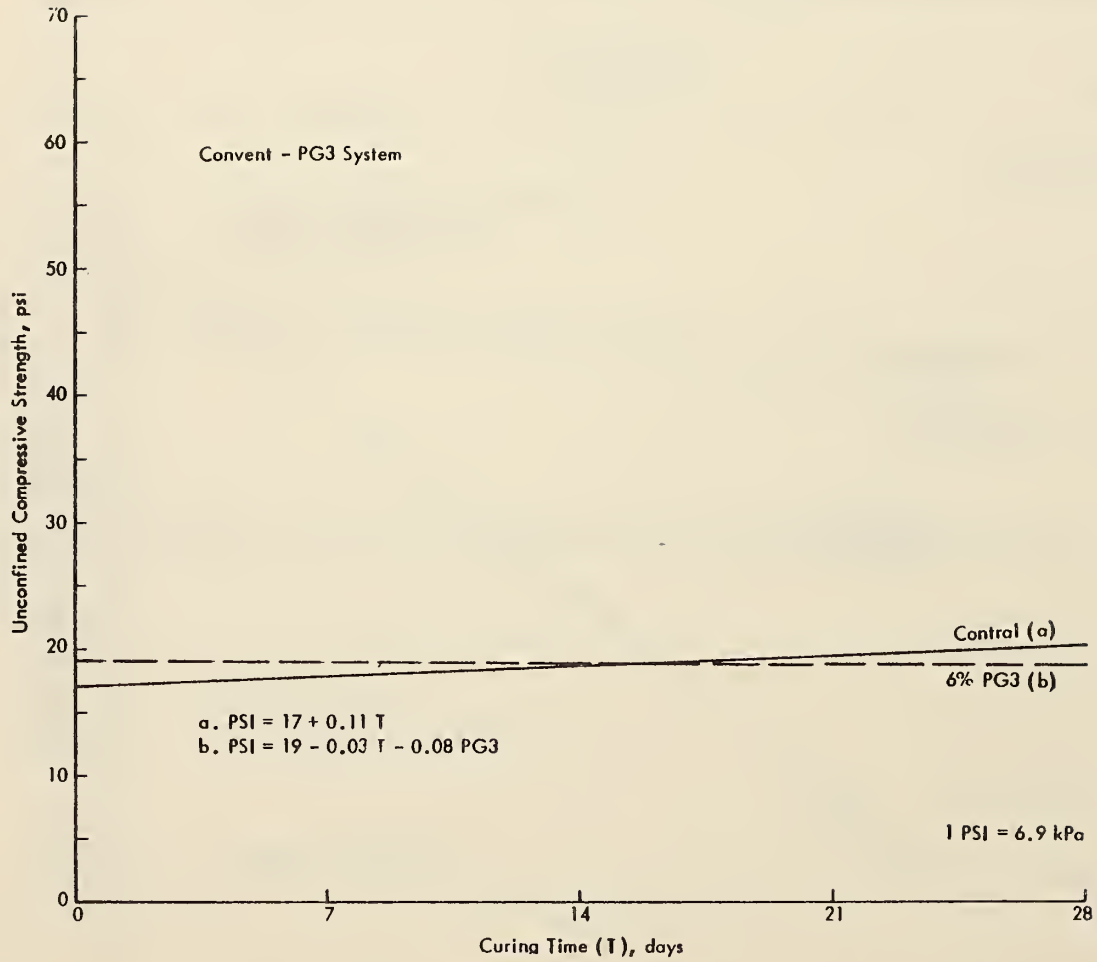

Figure 8. Linear regression plots of unconfined compressive strength versus curing time: Convent/PG3 system.

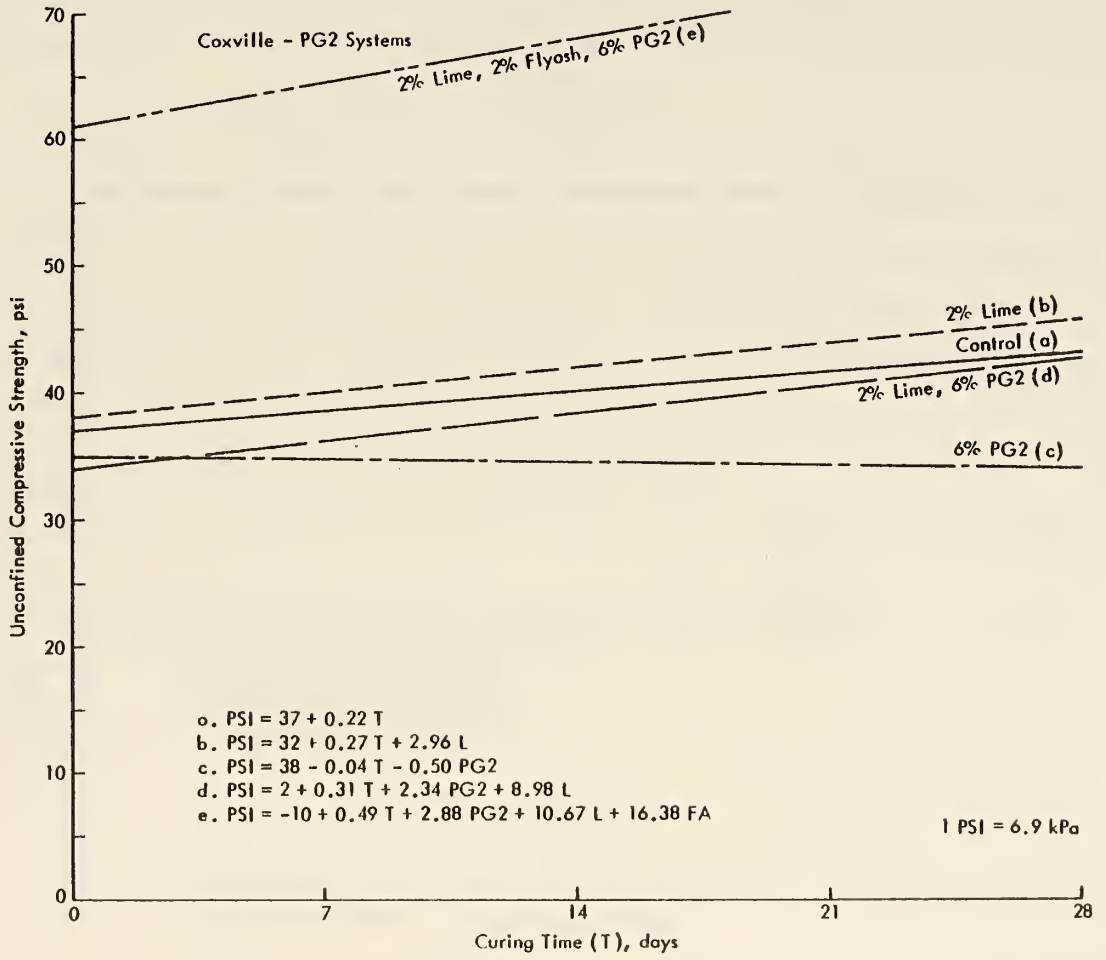

Figure 9. Linear regression plots of unconfined compressive strength versus curing time: Coxville/PG2 systems.

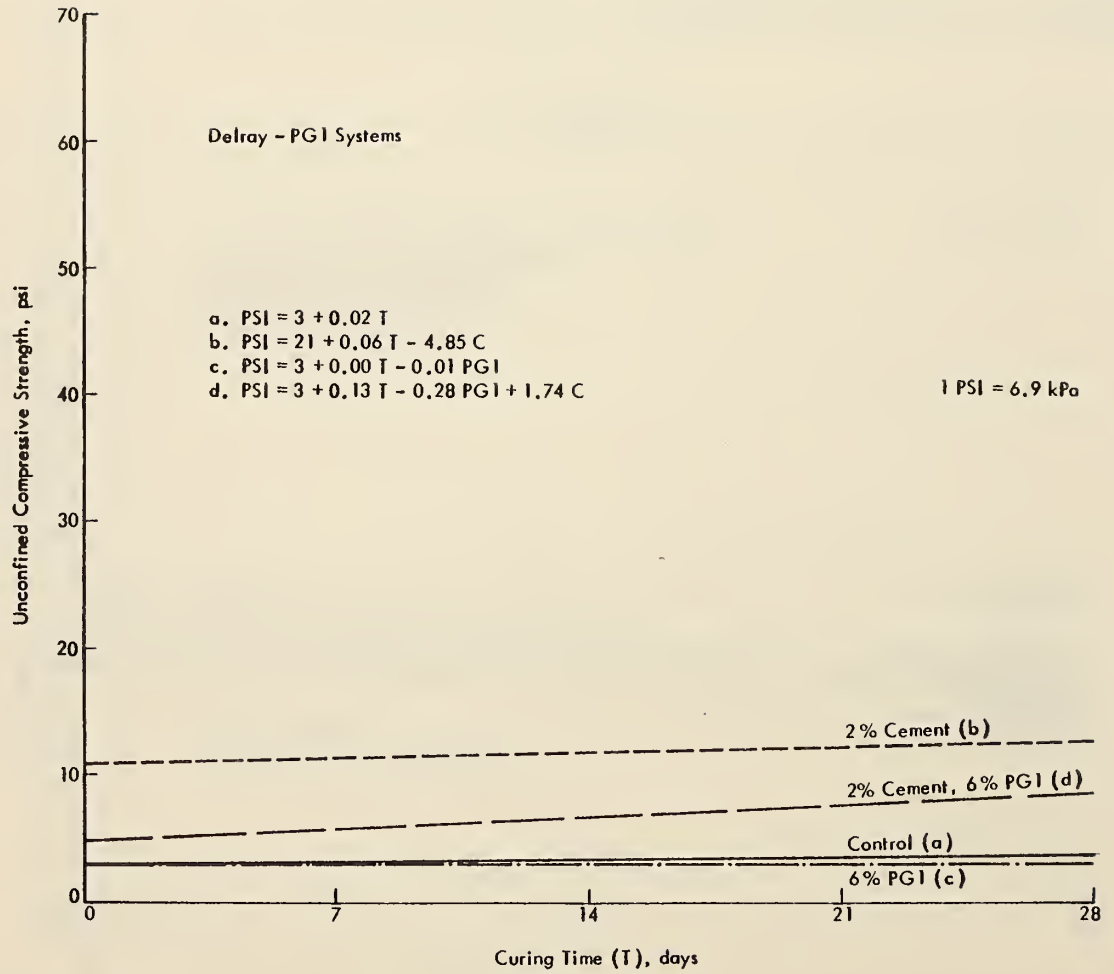

Figure 10. Linear regression plots of unconfined compressive strength versus curing time: Delray/PG1 systems.

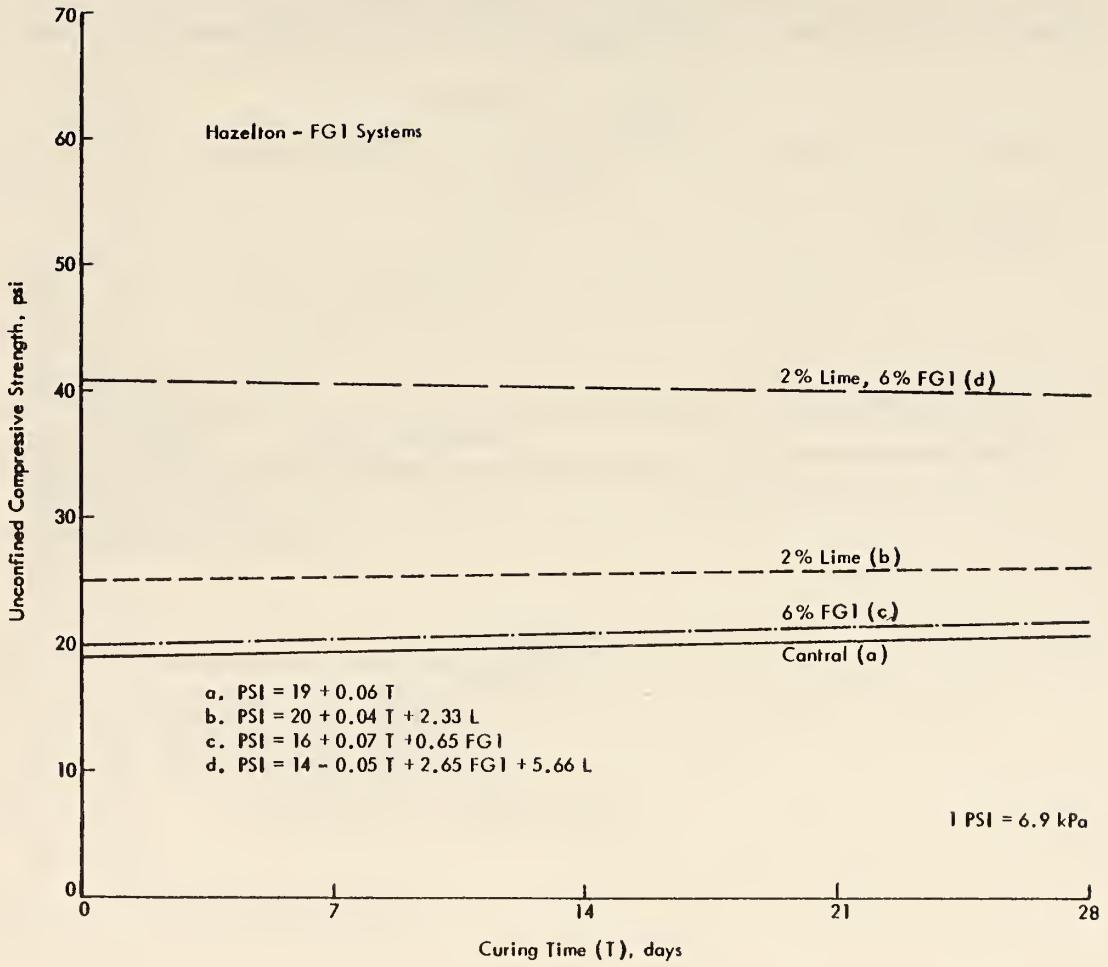

Figure 11. Linear regression plots of unconfined compressive strength versus curing time: Hazelton/FG1 systems.

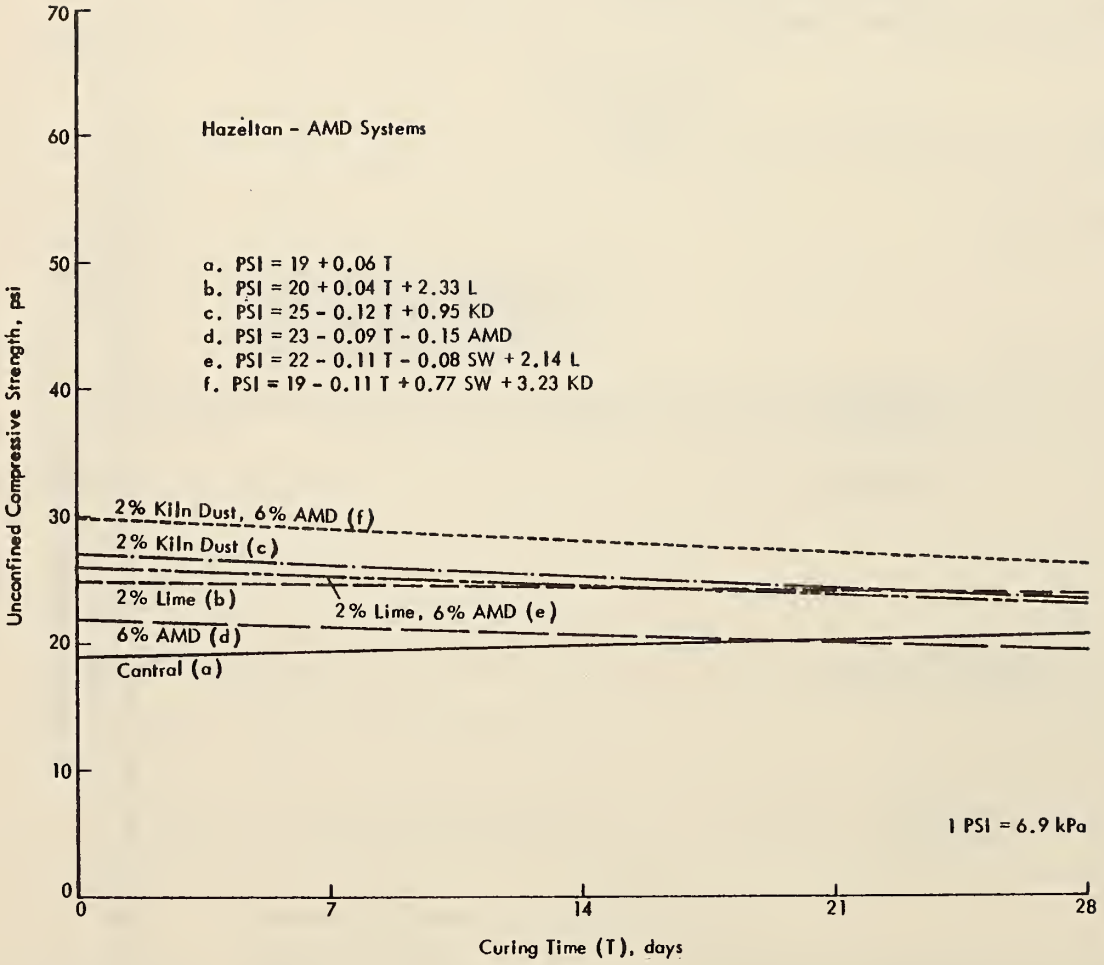
Hazeltan - AMD Systems
a. PSI = 19 + 0.06 T
b. PSI = 20 + 0.04 T + 2.33 L
c. PSI = 25 - 0.12 T + 0.95 KD
d. PSI = 23 - 0.09 T - 0.15 AMD
e. PSI = 22 - 0.11 T - 0.08 SW + 2.14 L
f. PSI = 19 - 0.11 T + 0.77 SW + 3.23 KD
2% Kiln Dust, 6% AMD (f)
2% Kiln Dust (c)
2% Lime (b)
2% Lime, 6% AMD (e)
6% AMD (d)
Control (a)
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 12. Linear regression plots of unconfined compressive strength versus curing time: Hazelton/AMD systems.

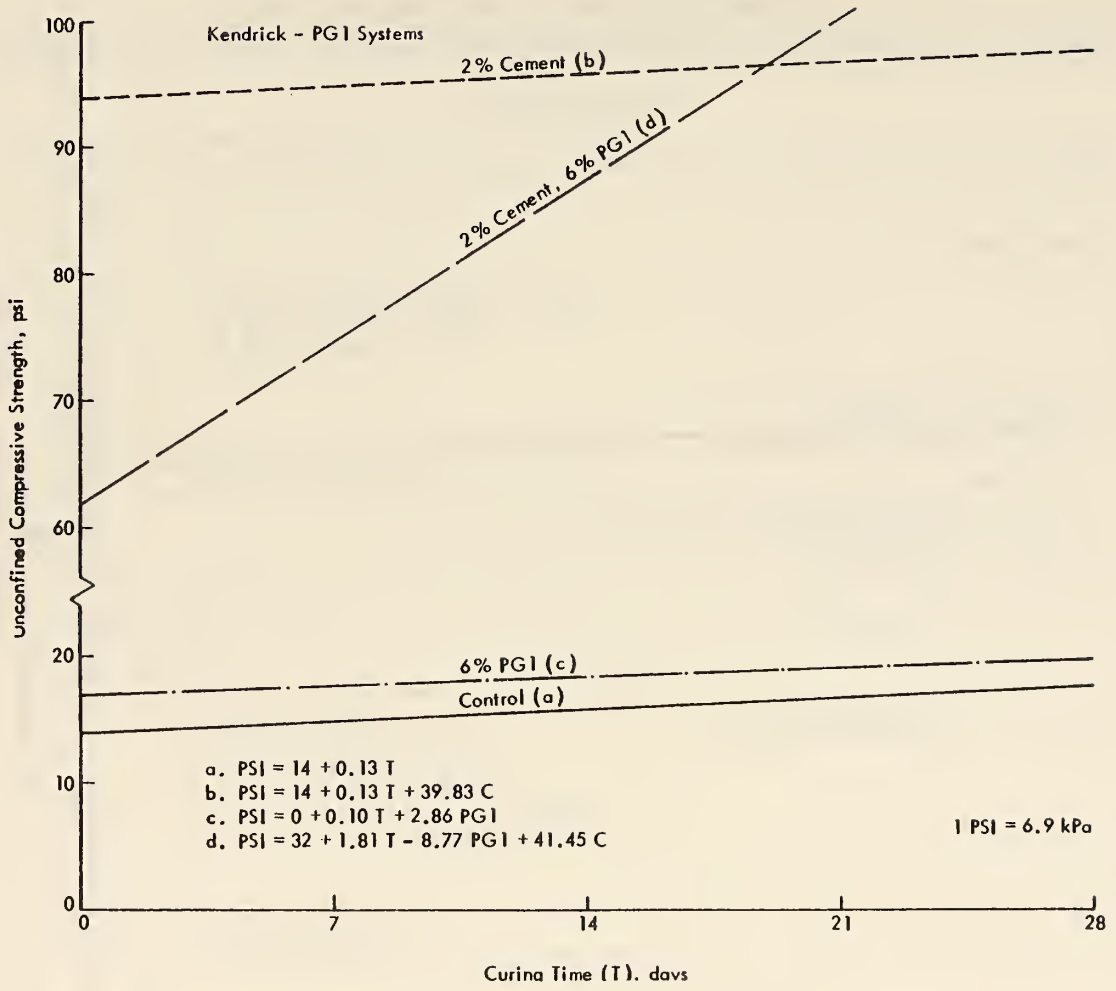

Figure 13. Linear regression plots of unconfined compressive strength versus curing time: Kendrick/PG1 systems.

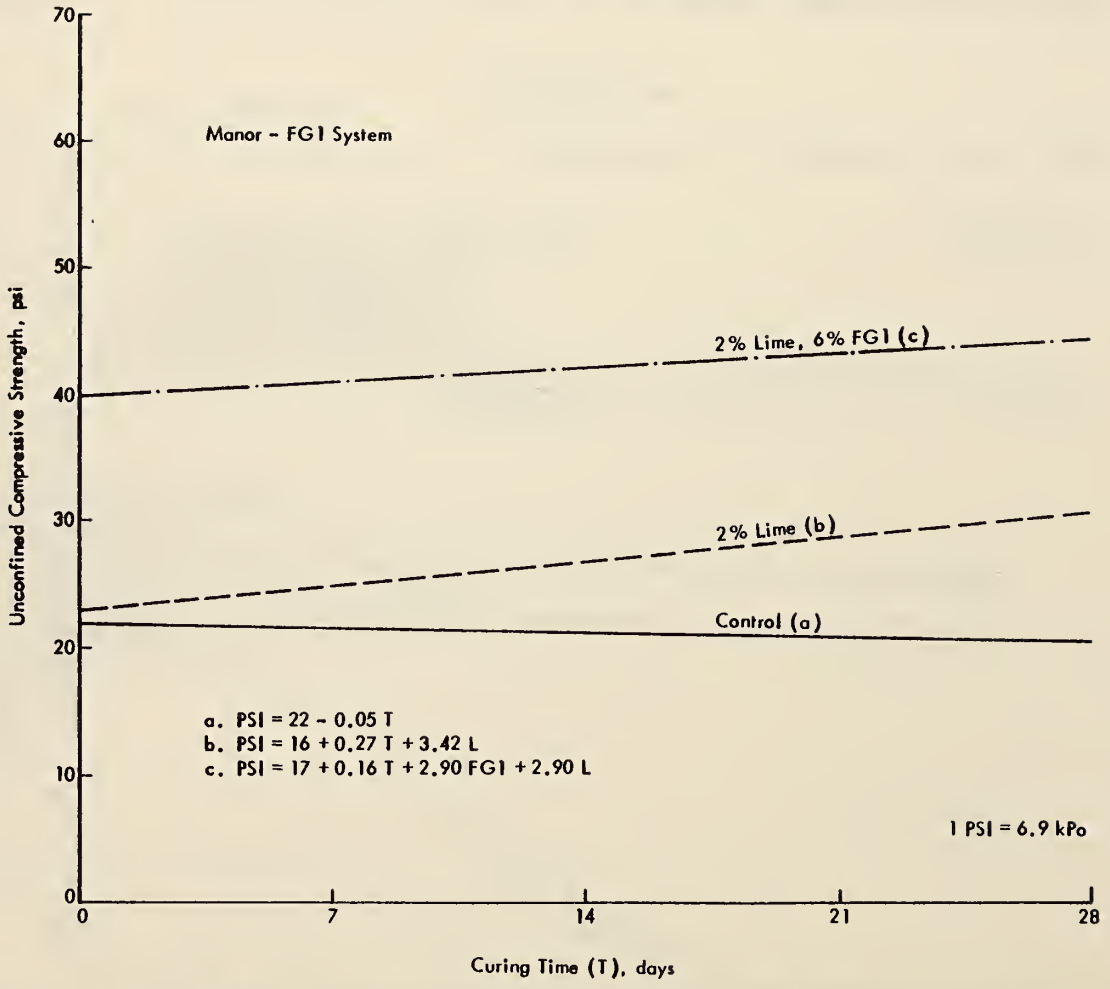

Figure 14. Linear regression plots of unconfined compressive strength versus curing time: Manor/FG1 system.

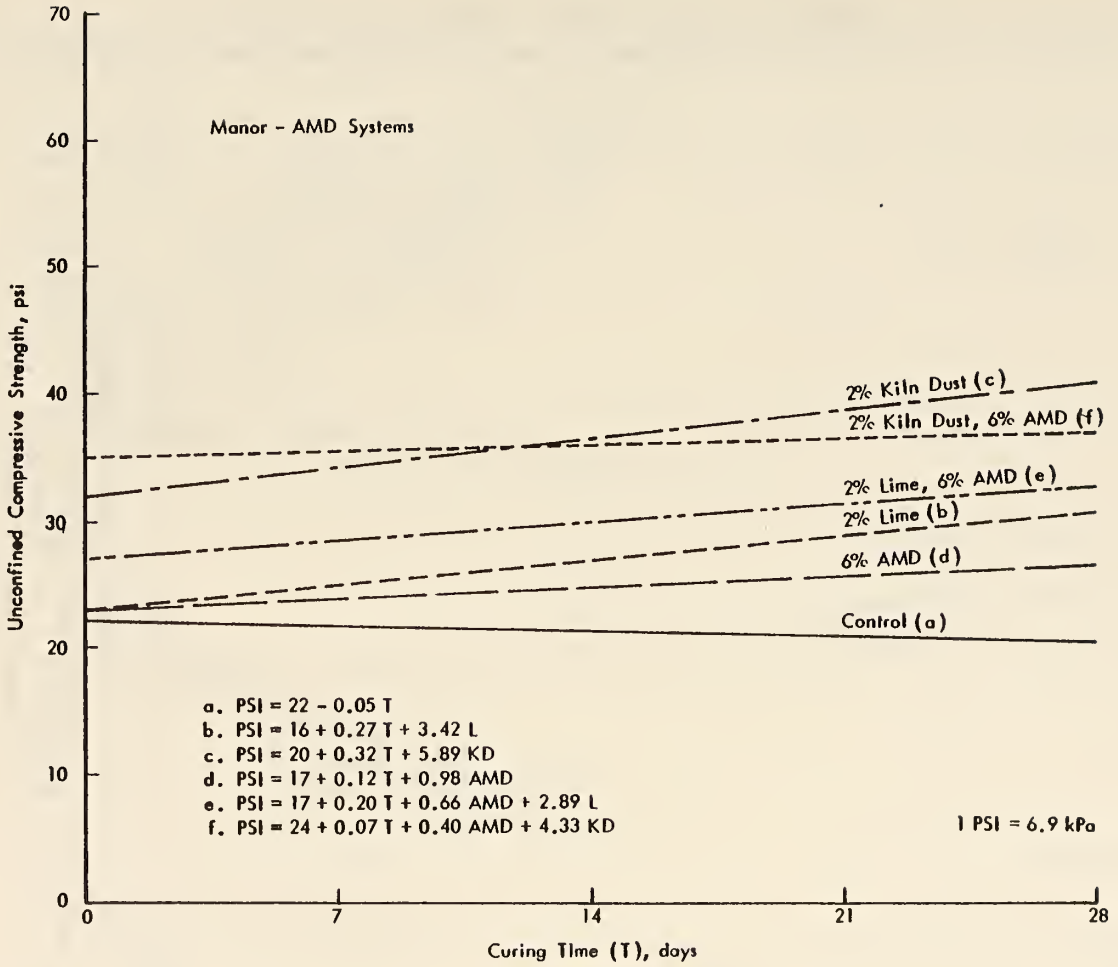
Manor - AMD Systems
Unconfined Compressive Strength, psi
70
60
50
40
30
20
10
0
0
7
14
21
28
Curing Time (T), days
2% Kiln Dust (c)
2% Kiln Dust, 6% AMD (f)
2% Lime, 6% AMD (e)
2% Lime (b)
6% AMD (d)
Control (a)
a. PSI = 22 - 0.05 T
b. PSI = 16 + 0.27 T + 3.42 L
c. PSI = 20 + 0.32 T + 5.89 KD
d. PSI = 17 + 0.12 T + 0.98 AMD
e. PSI = 17 + 0.20 T + 0.66 AMD + 2.89 L
f. PSI = 24 + 0.07 T + 0.40 AMD + 4.33 KD
1 PSI = 6.9 kPa

Figure 15. Linear regression plots of unconfined compressive strength versus curing time: Manor/AMD systems.

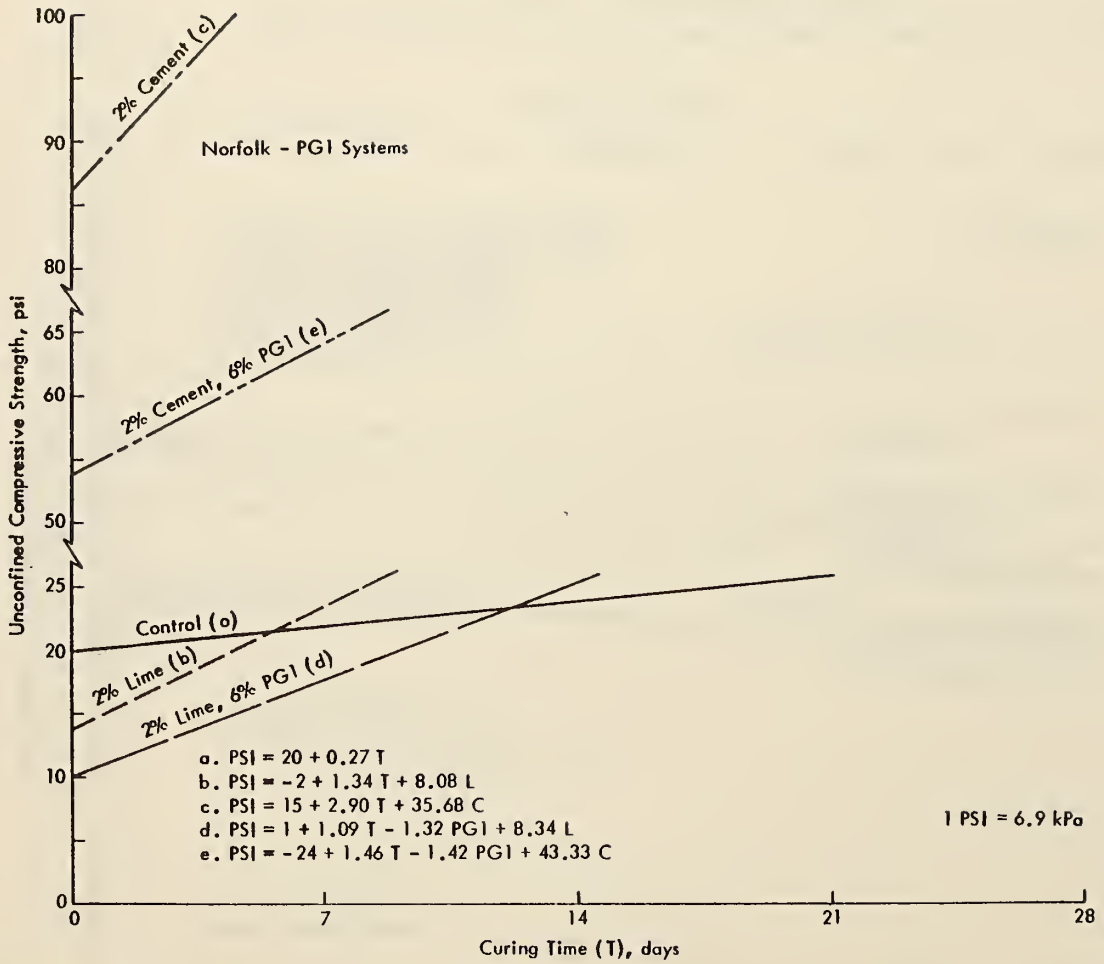

Figure 16. Linear regression plots of unconfined compressive strength versus curing time: Norfolk/PG1 systems.

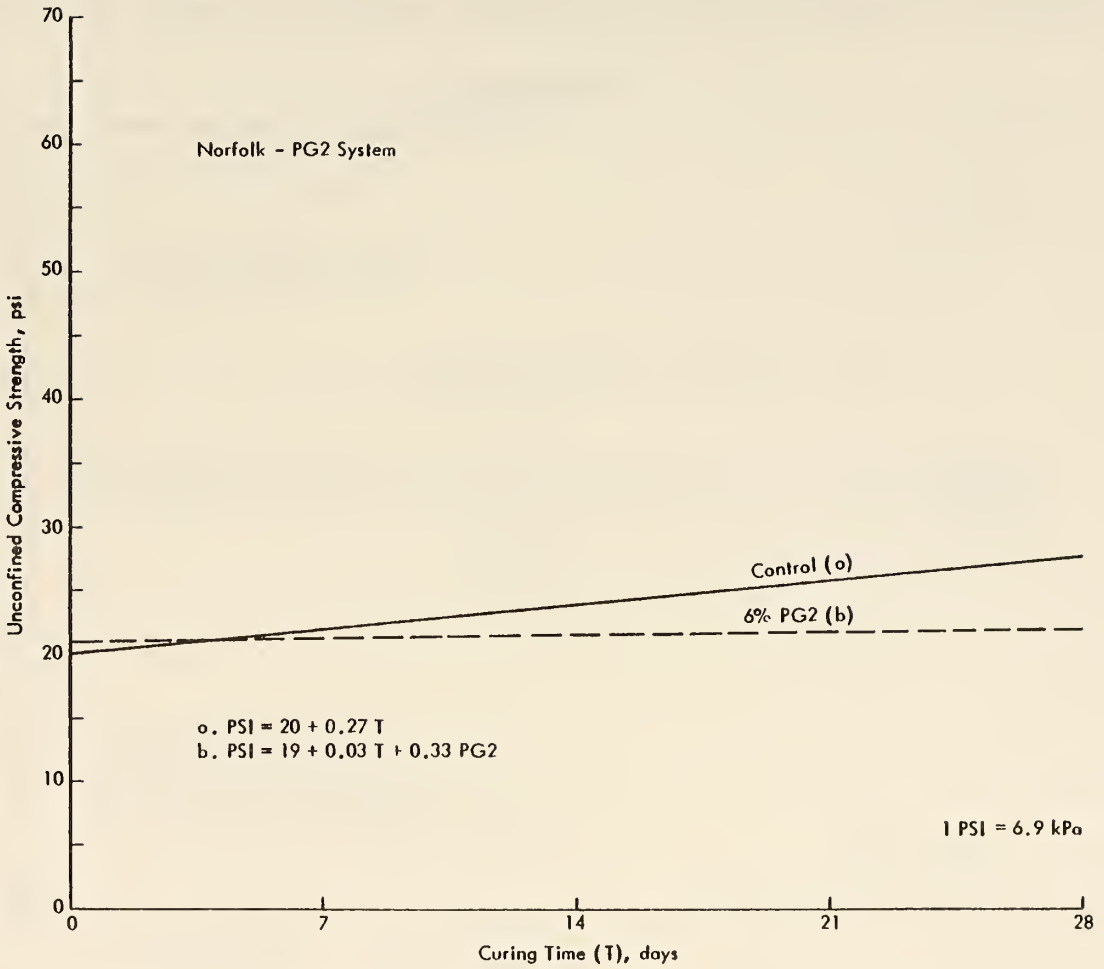

Figure 17. Linear regression plots of unconfined compressive strength versus curing time: Norfolk/PG2 system.

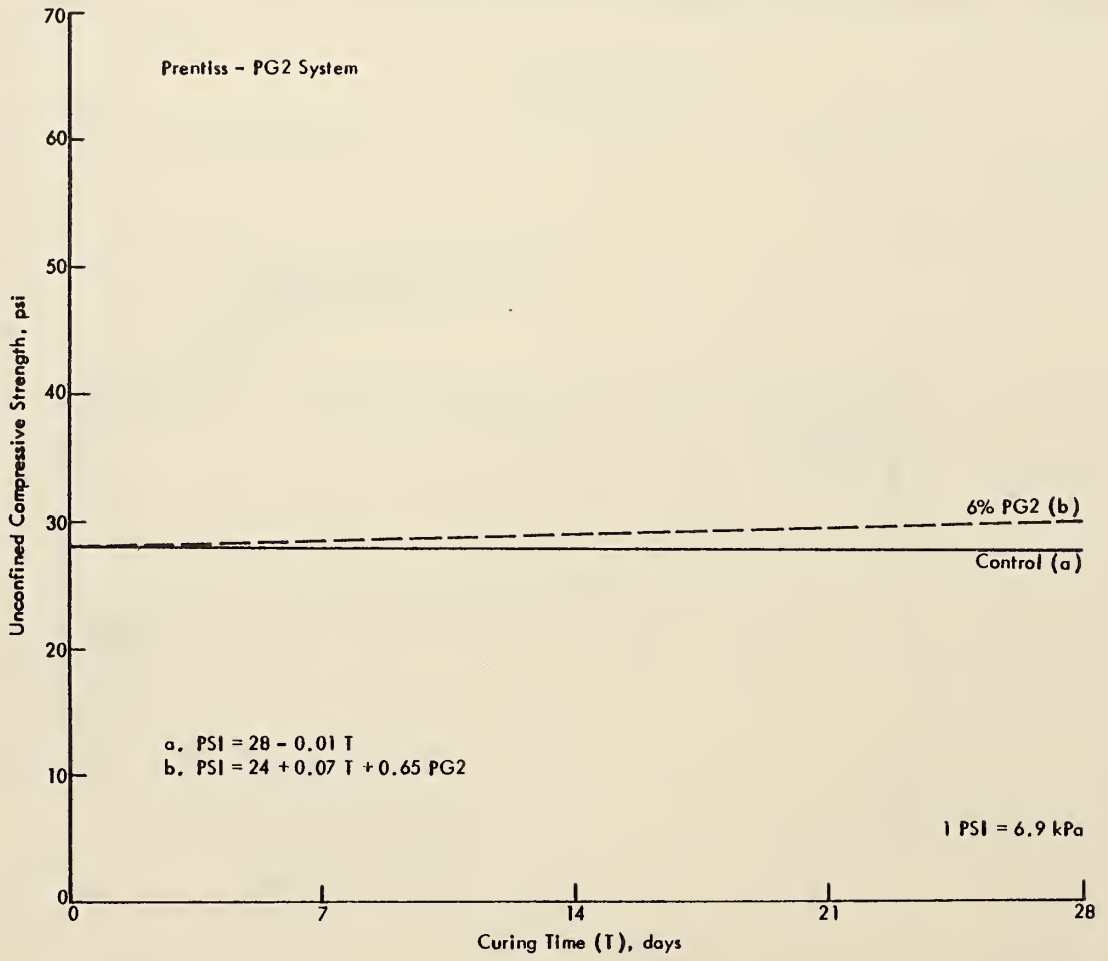

Figure 18. Linear regression plots of unconfined compressive strength versus curing time: Prentiss/PG2 system.

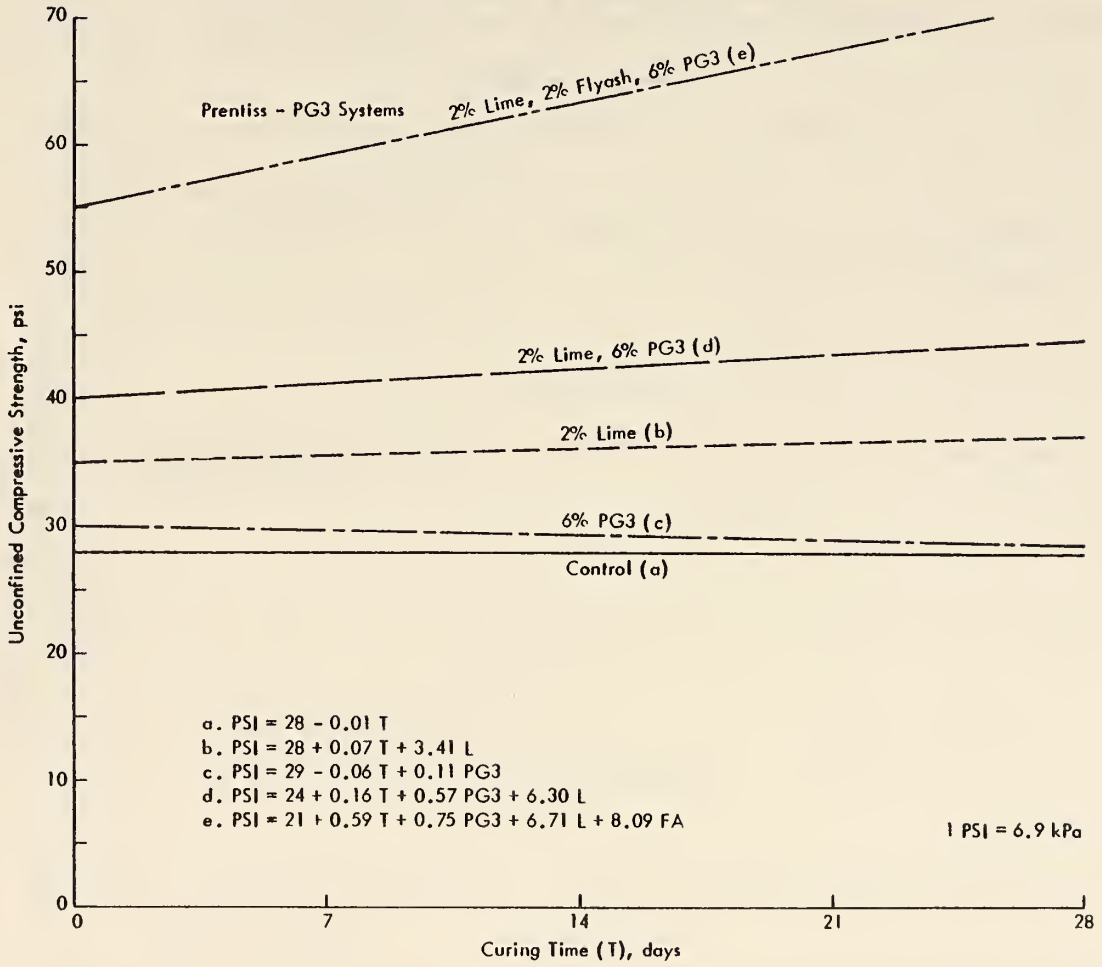

Figure 19. Linear regression plots of unconfined compressive strength versus curing time: Prentiss/PG3 systems.

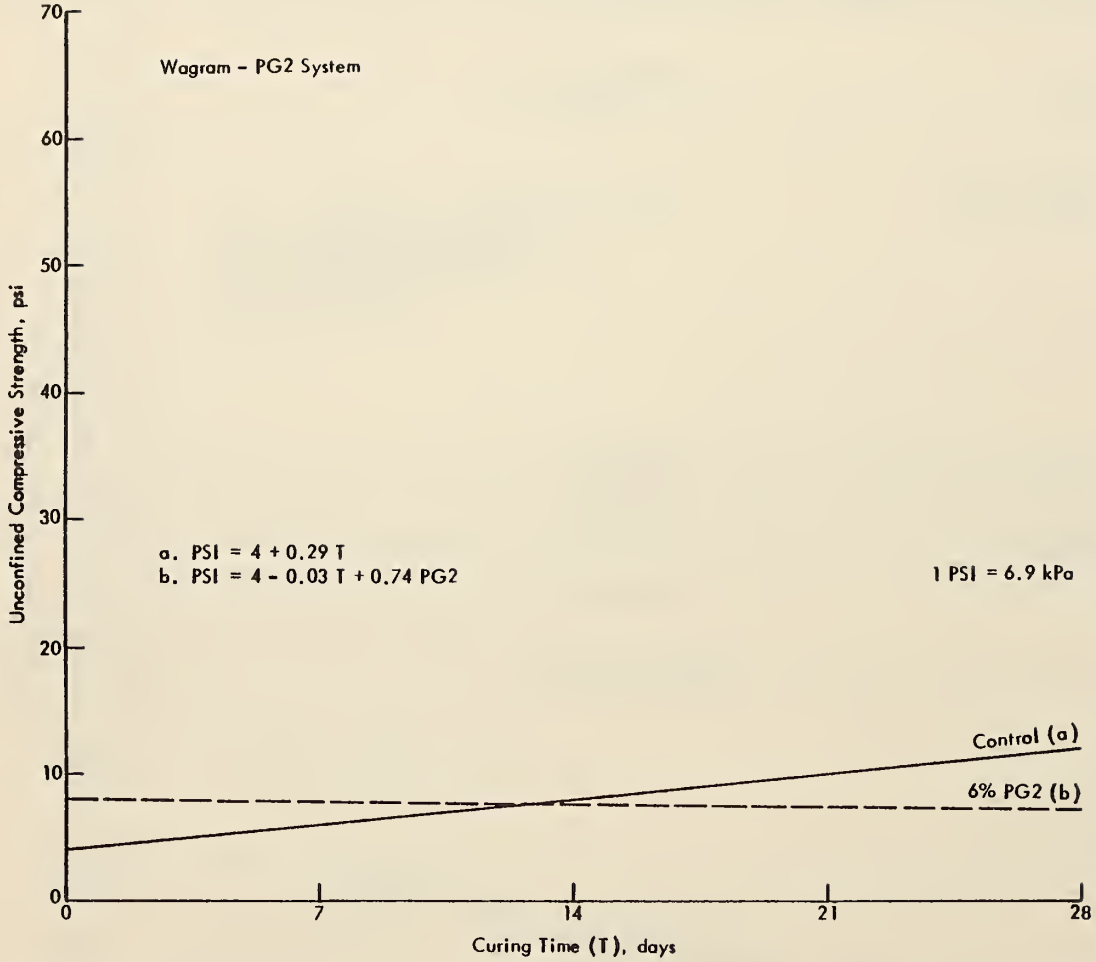

Figure 20. Linear regression plots of unconfined compressive strength versus curing time: Wagram/PG2 system.

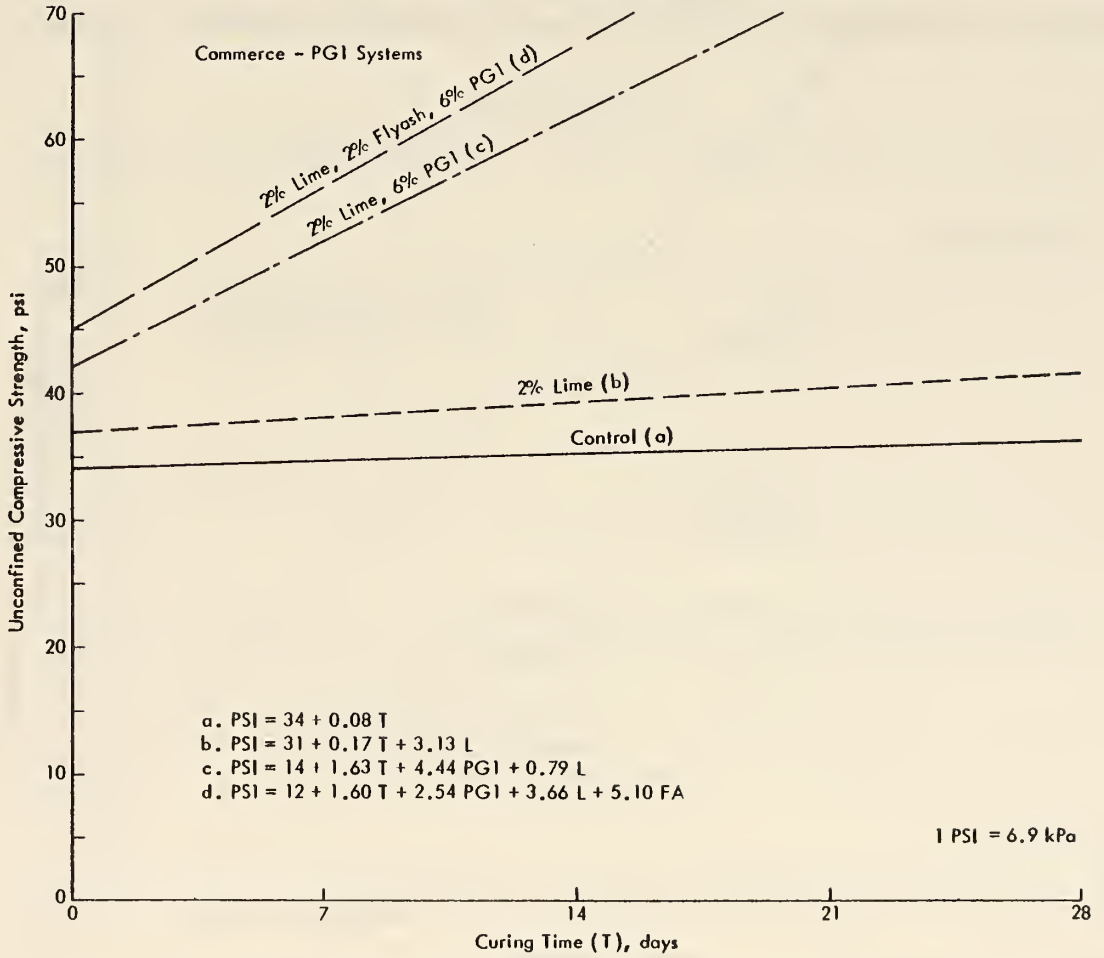

Figure 21. Linear regression plots of unconfined compressive strength versus curing time: Commerce/PG1 systems.

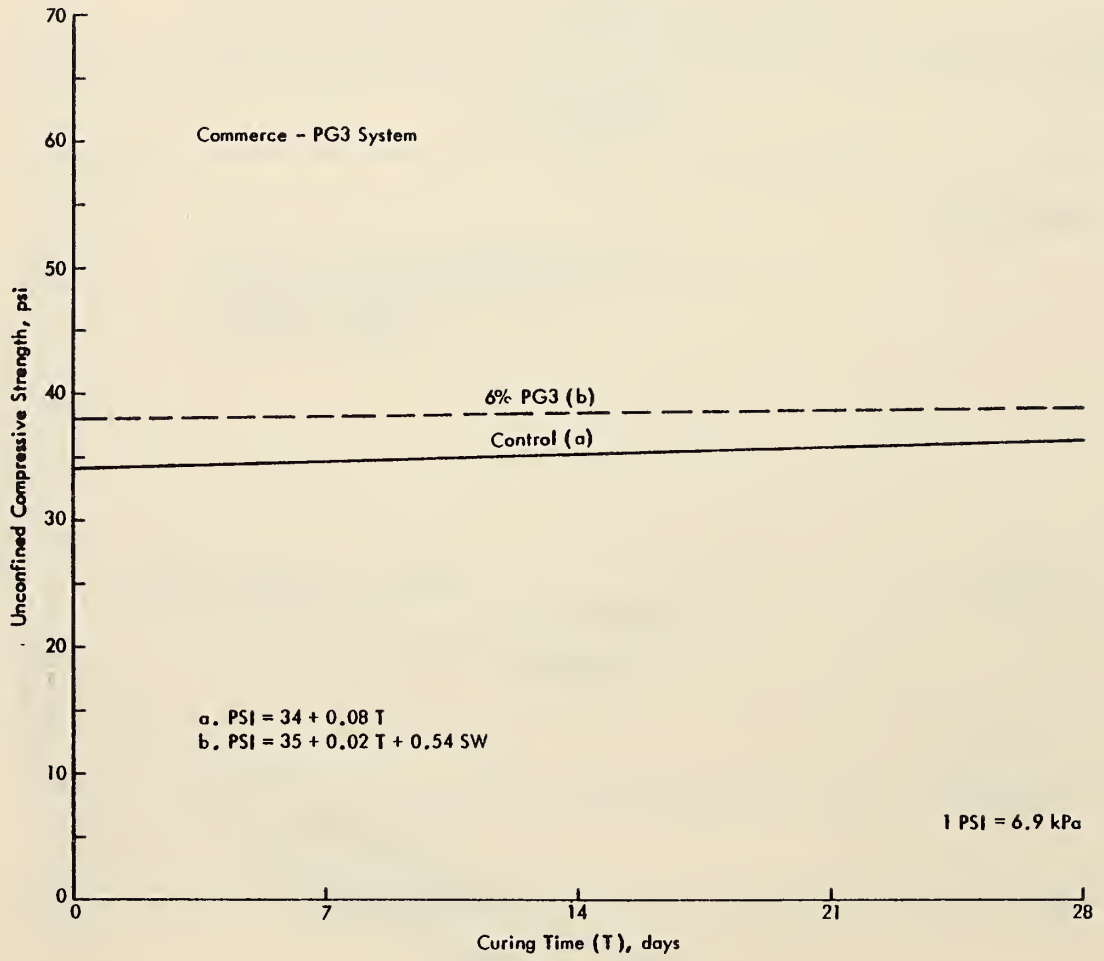

Figure 22. Linear regression plots of unconfined compressive strength versus curing time: Commerce/PG3 system.

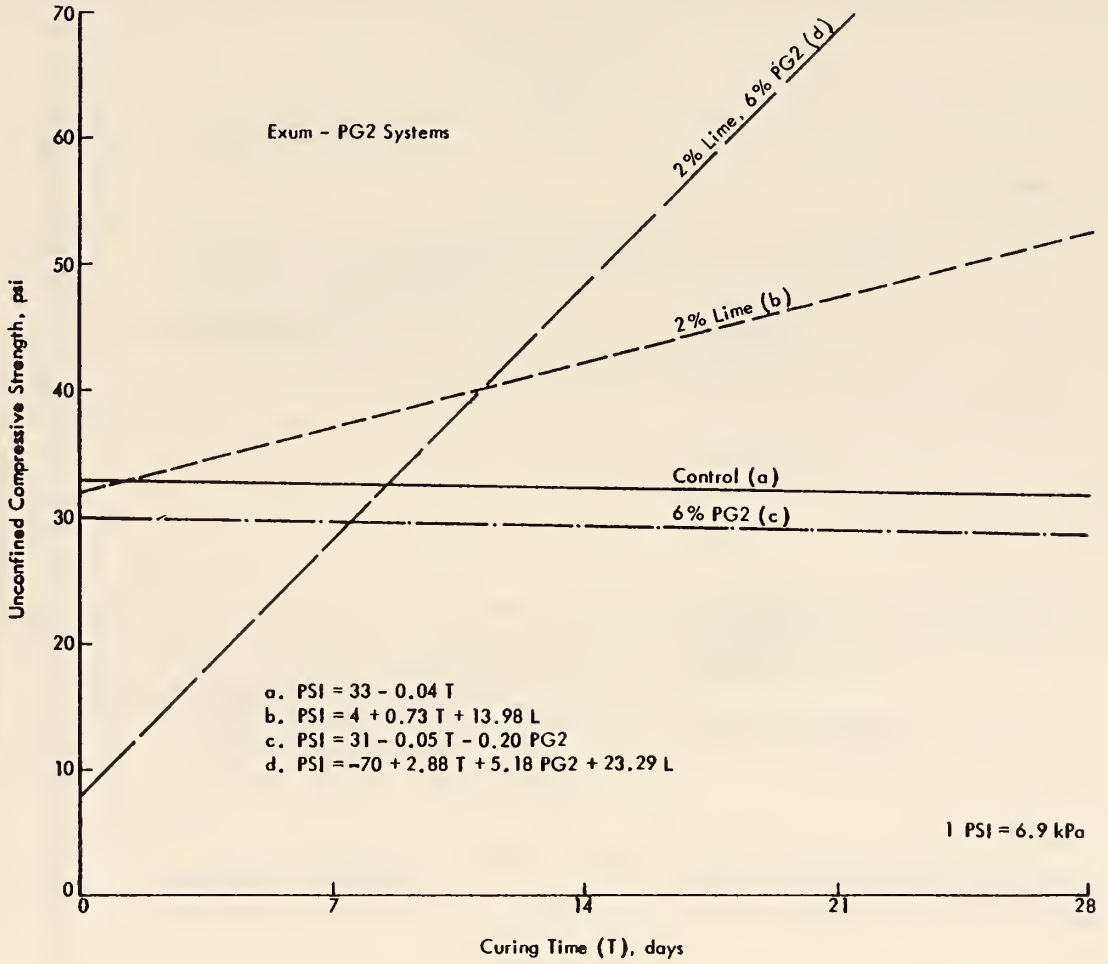

Figure 23. Linear regression plots of unconfined compressive strength versus curing time: Exum/PG2 systems.

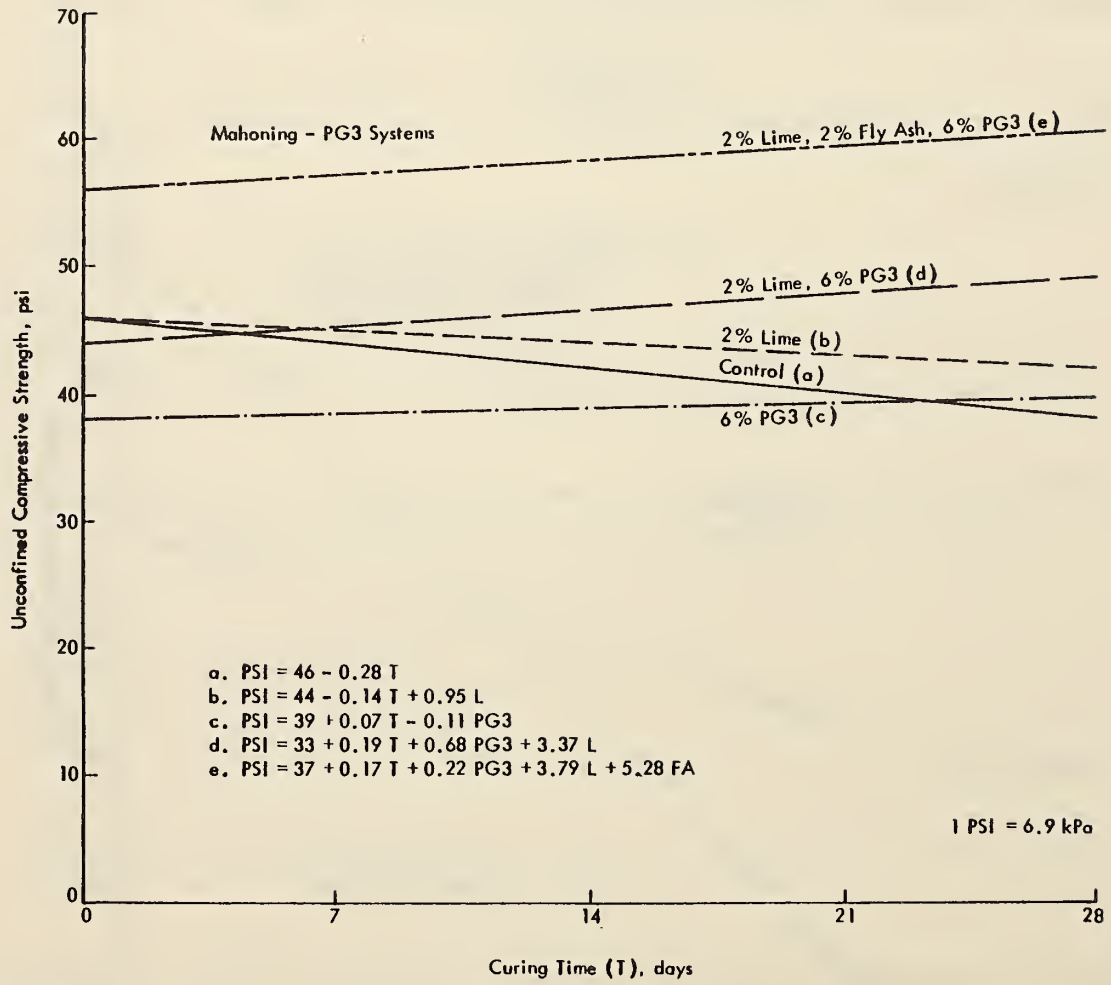
Mahoning - PG3 Systems
2% Lime, 2% Fly Ash, 6% PG3 (e)
2% Lime, 6% PG3 (d)
2% Lime (b)
Control (a)
6% PG3 (c)
a. PSI = 46 - 0.28 T
b. PSI = 44 - 0.14 T + 0.95 L
c. PSI = 39 + 0.07 T - 0.11 PG3
d. PSI = 33 + 0.19 T + 0.68 PG3 + 3.37 L
e. PSI = 37 + 0.17 T + 0.22 PG3 + 3.79 L + 5.28 FA
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 24. Linear regression plots of unconfined compressive strength versus curing time: Mahoning/PG3 systems.

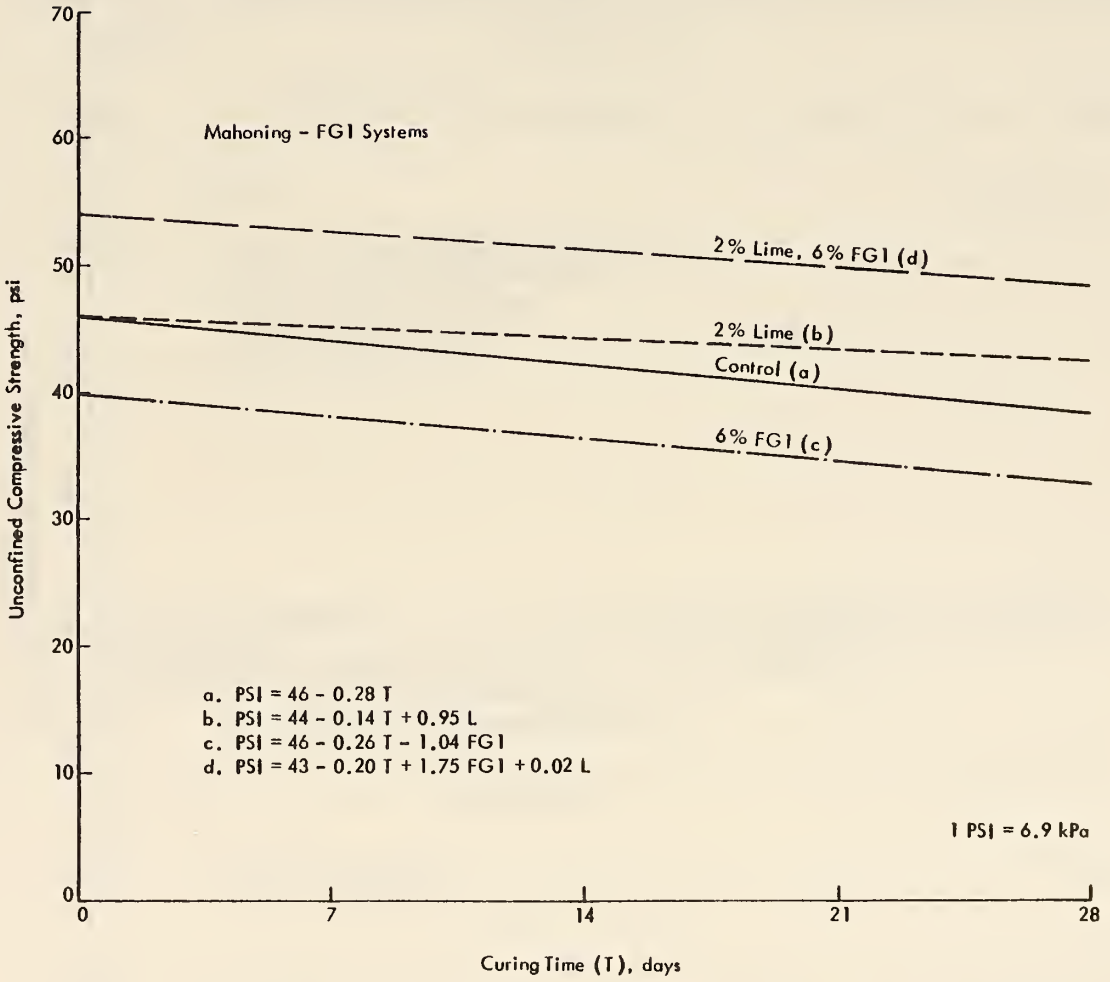

Figure 25. Linear regression plots of unconfined compressive strength versus curing time: Mahoning/FG1 systems.

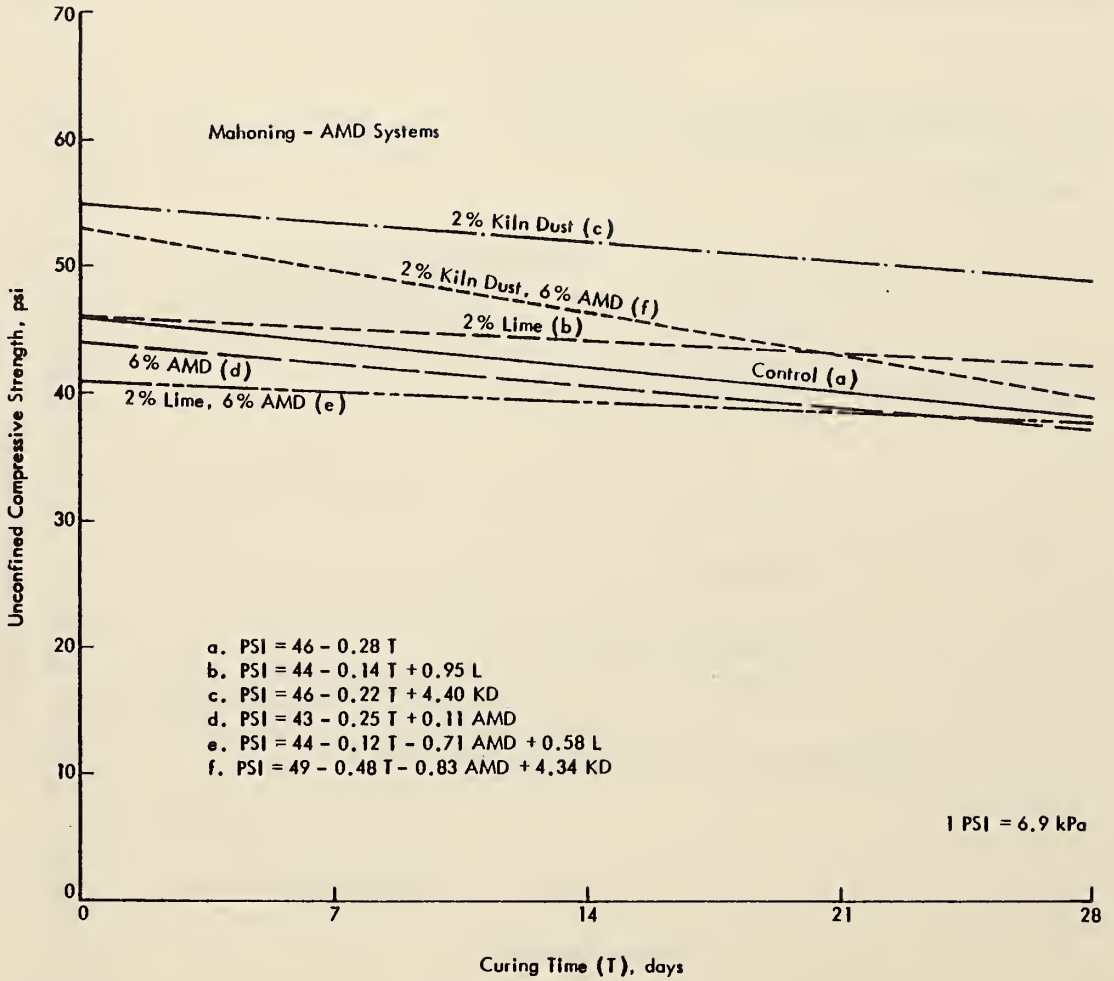
Mahoning - AMD Systems
2% Kiln Dust (c)
2% Kiln Dust, 6% AMD (f)
2% Lime (b)
Control (a)
6% AMD (d)
2% Lime, 6% AMD (e)
a. PSI = 46 - 0.28 T
b. PSI = 44 - 0.14 T + 0.95 L
c. PSI = 46 - 0.22 T + 4.40 KD
d. PSI = 43 - 0.25 T + 0.11 AMD
e. PSI = 44 - 0.12 T - 0.71 AMD + 0.58 L
f. PSI = 49 - 0.48 T - 0.83 AMD + 4.34 KD
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 26. Linear regression plots of unconfined compressive strength versus curing time: Mahoning/AMD systems.

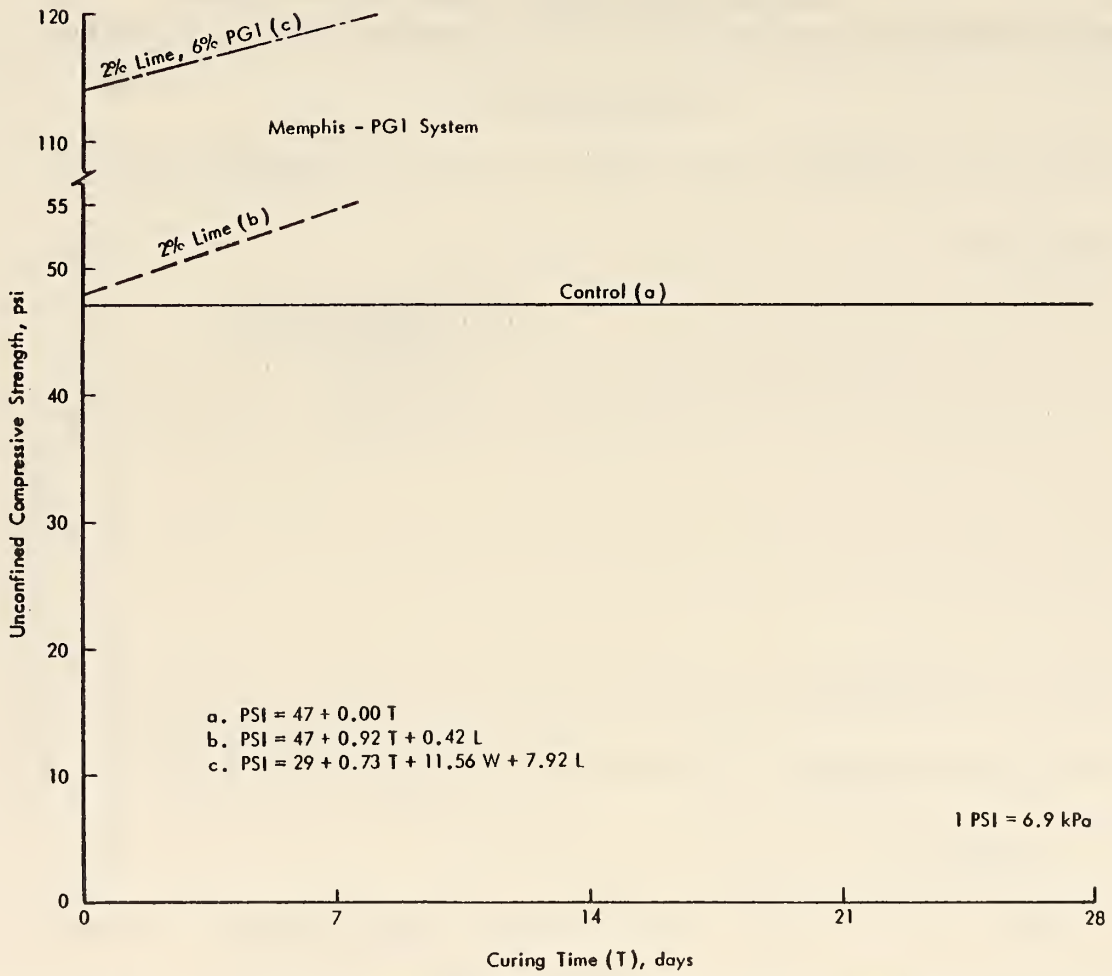

Figure 27. Linear regression plots of unconfined compressive strength versus curing time: Memphis/PG1 system.

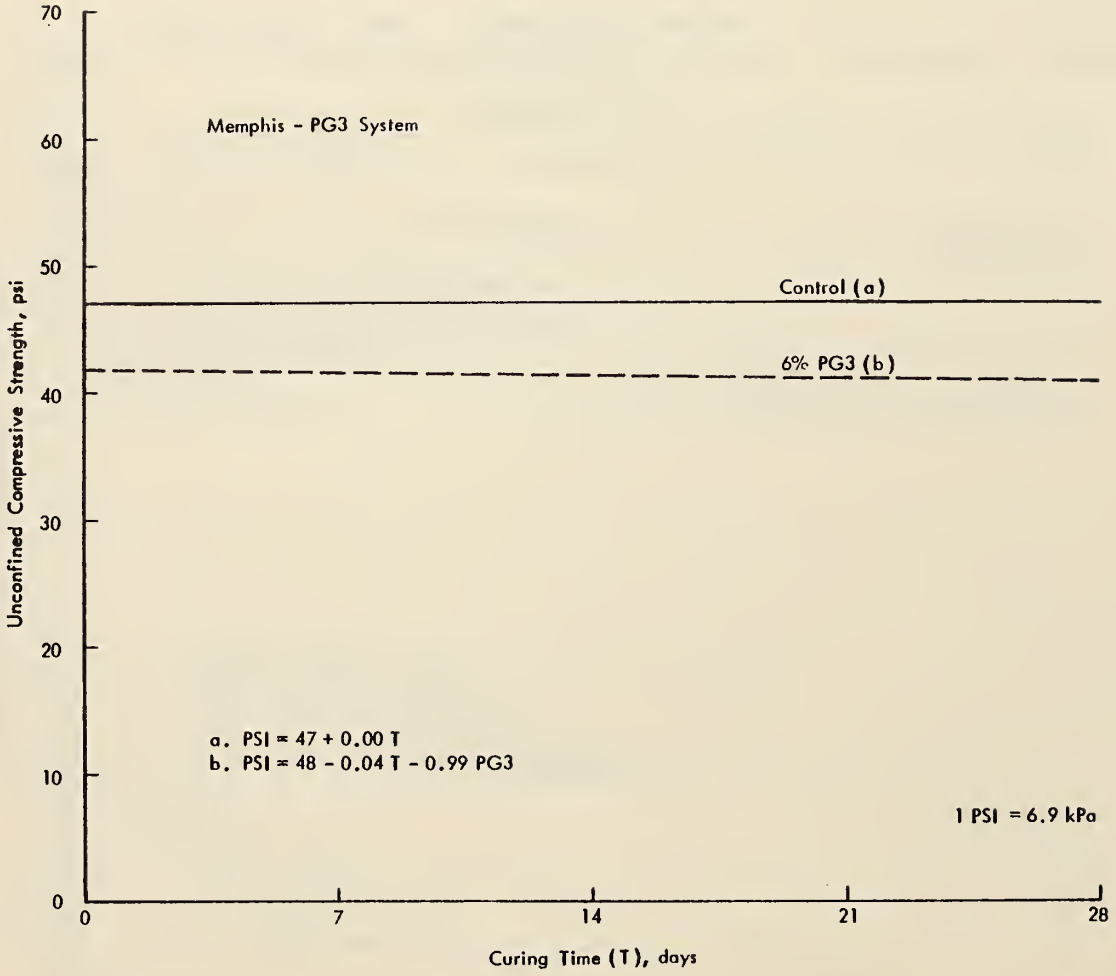

Figure 28. Linear regression plots of unconfined compressive strength versus curing time: Memphis/PG3 system.

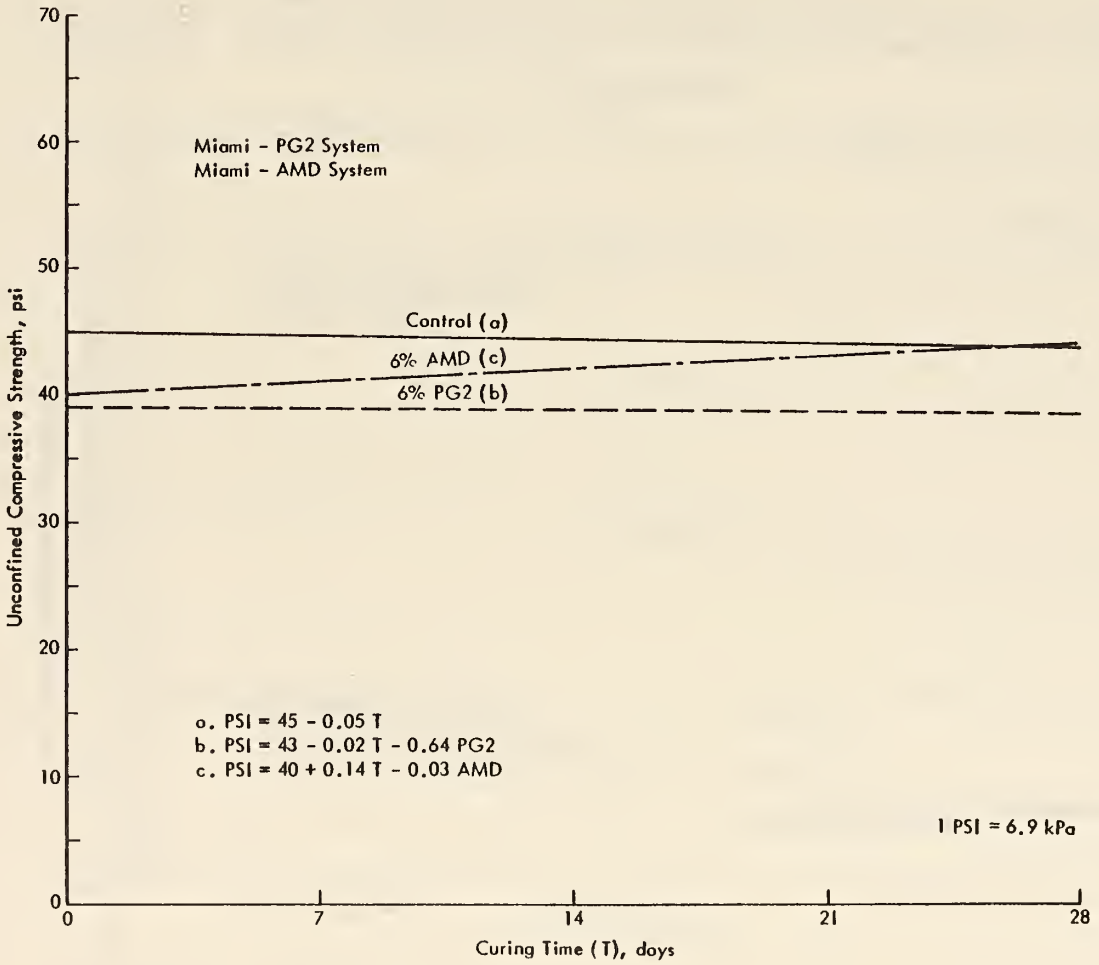

Figure 29. Linear regression plots of unconfined compressive strength versus curing time: Miami/PG2 and Miami/AMD systems.

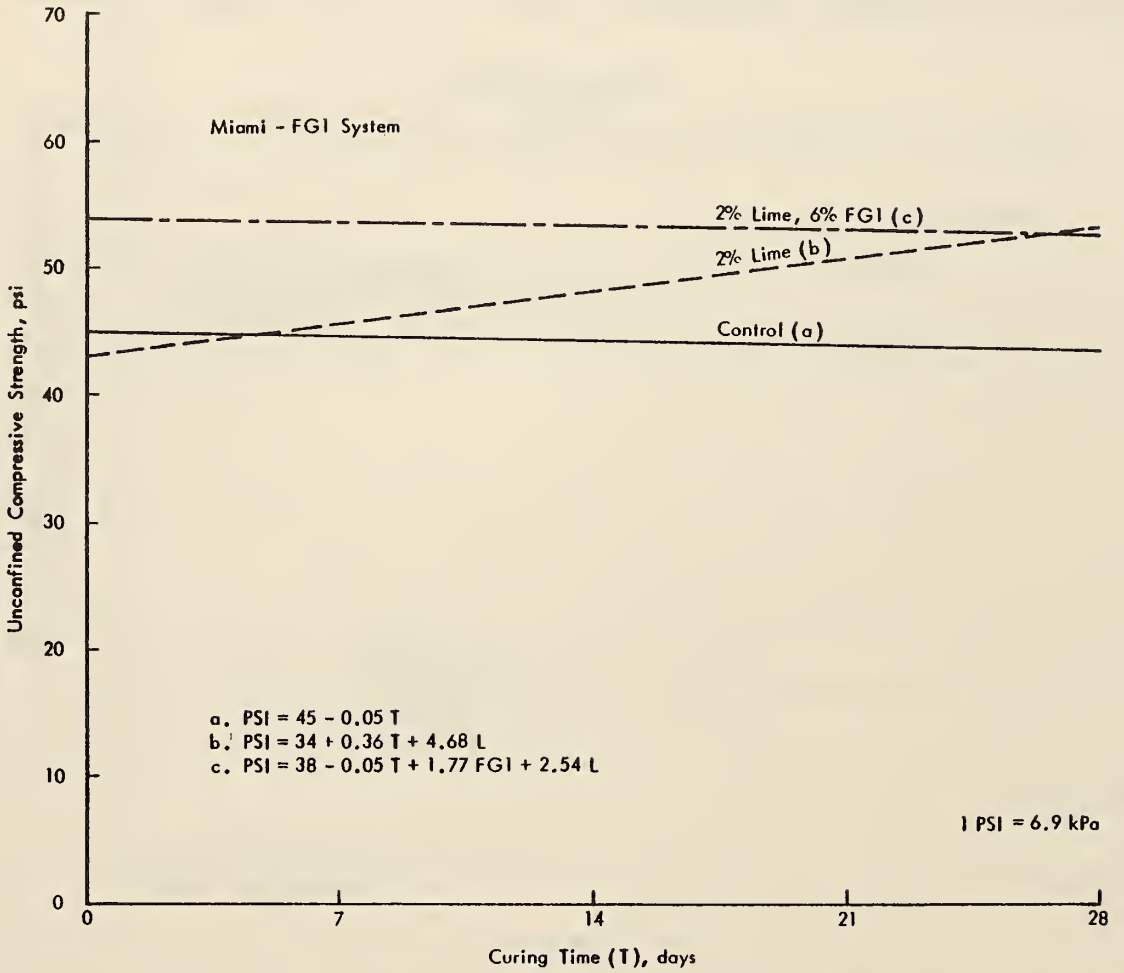

Figure 30. Linear regression plots of unconfined compressive strength versus curing time: Miami/FG1 system.

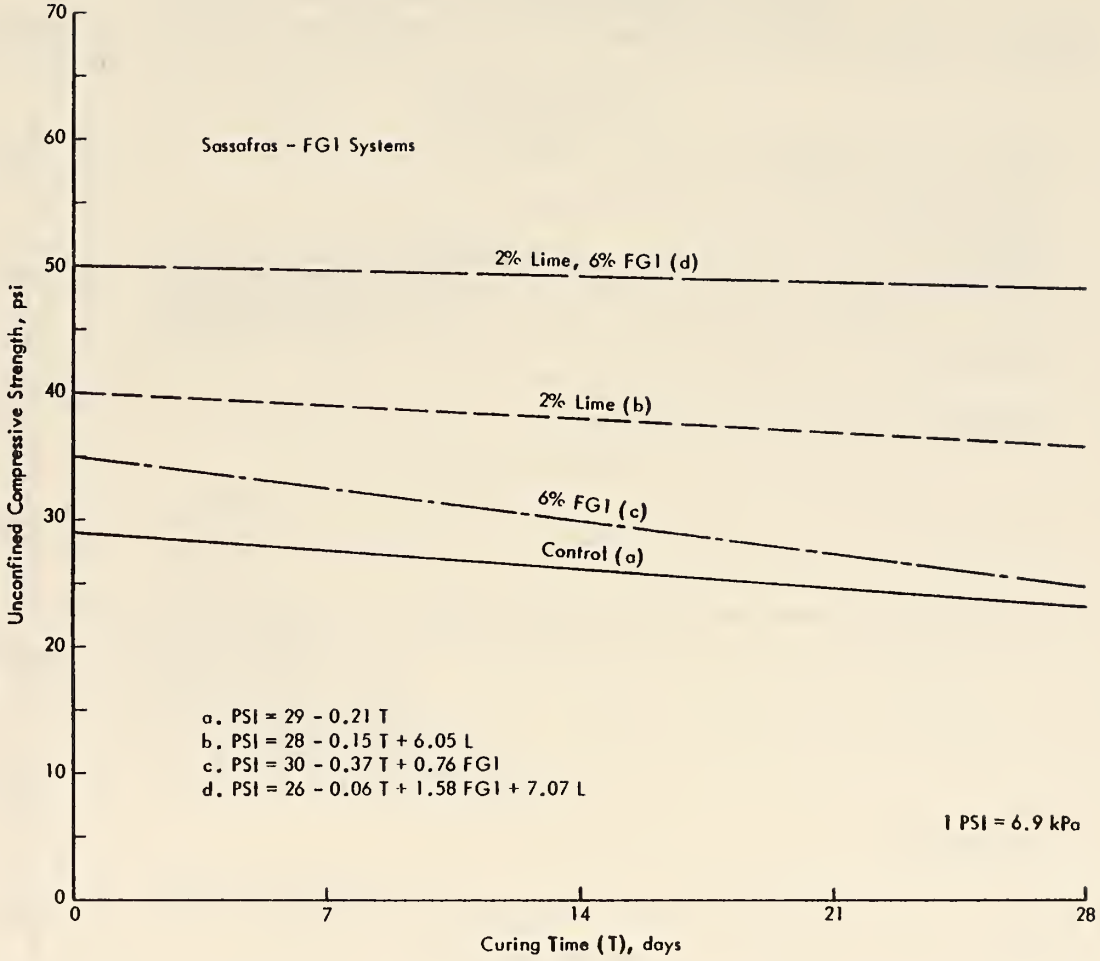

Figure 31. Linear regression plots of unconfined compressive strength versus curing time: Sassafras/FGl systems.

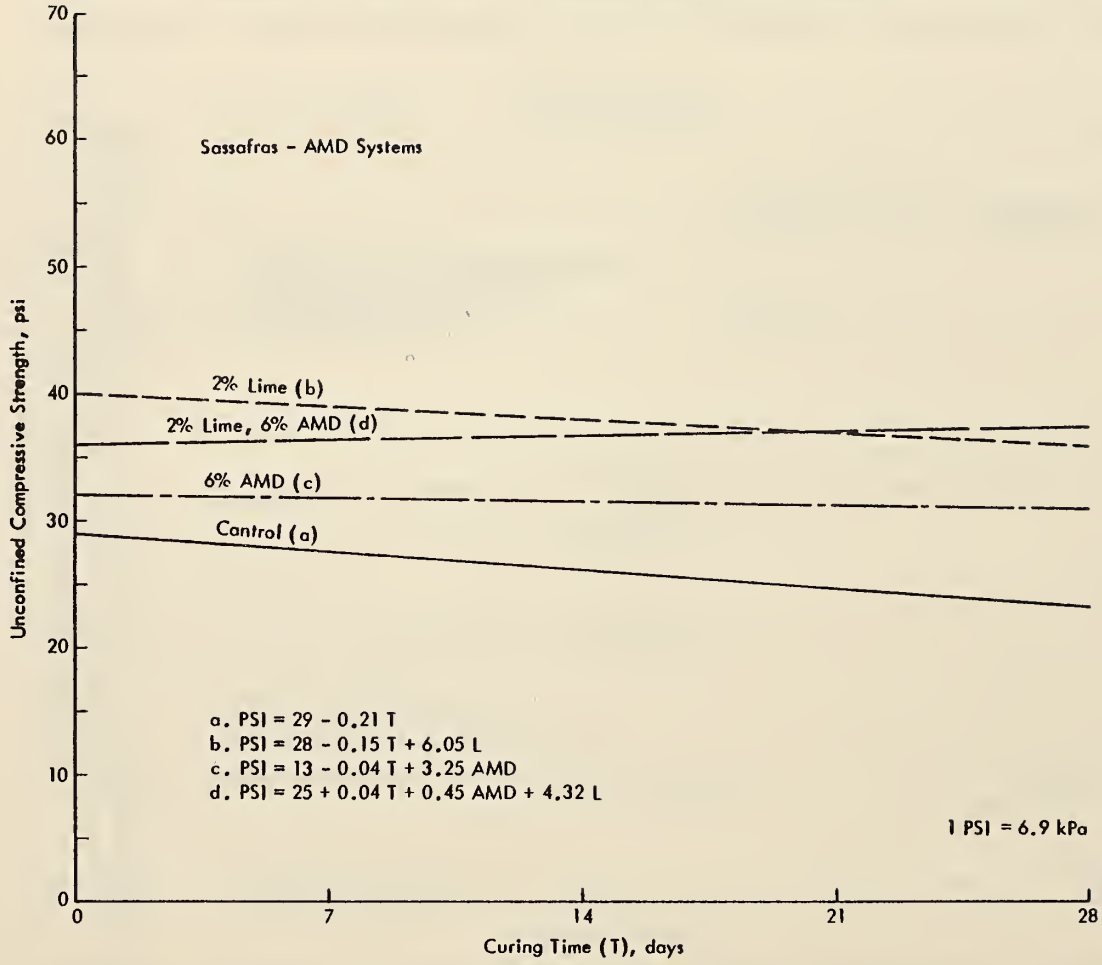

Figure 32. Linear regression plots of unconfined compressive strength versus curing time: Sassafras/AMD systems.

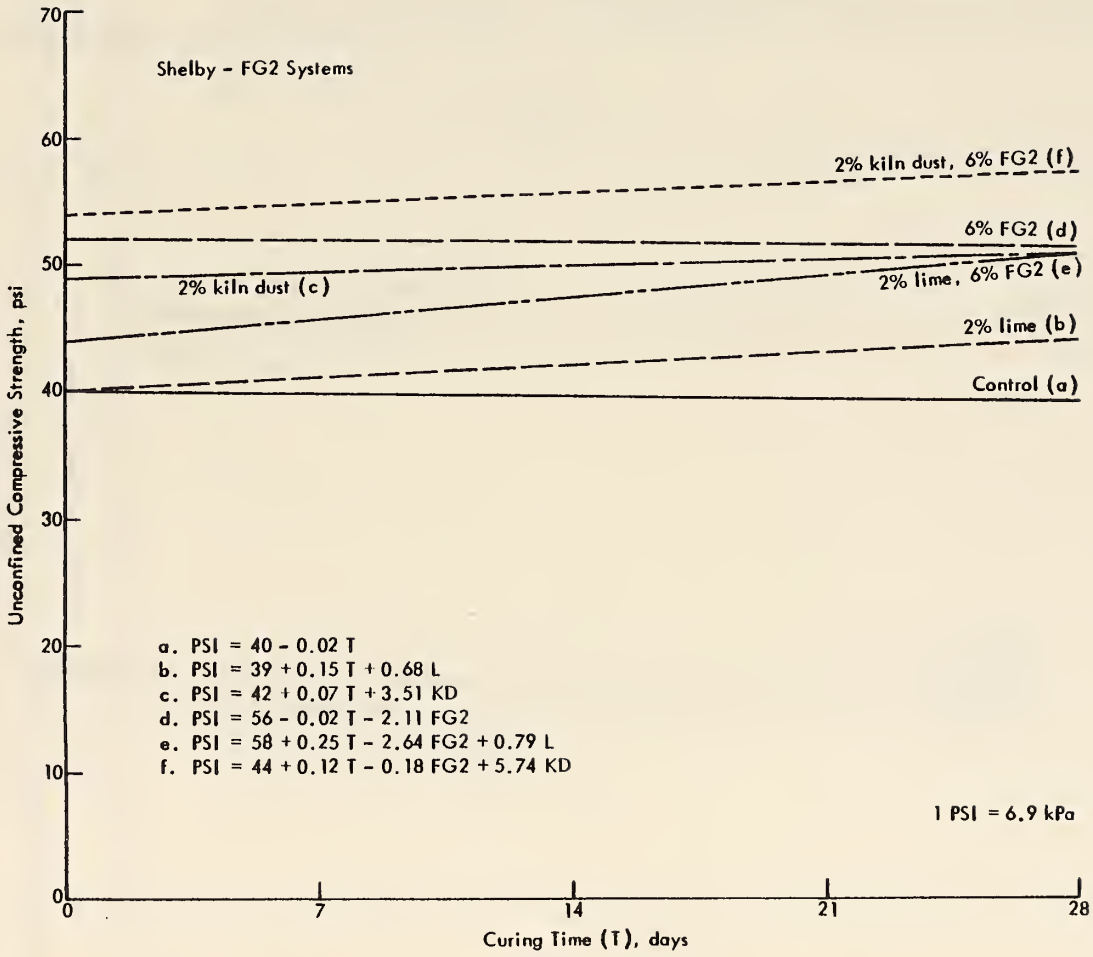
Shelby - FG2 Systems
2% kiln dust, 6% FG2 (f)
6% FG2 (d)
2% kiln dust (c)
2% lime, 6% FG2 (e)
2% lime (b)
Control (a)
a. PSI = 40 - 0.02 T
b. PSI = 39 + 0.15 T + 0.68 L
c. PSI = 42 + 0.07 T + 3.51 KD
d. PSI = 56 - 0.02 T - 2.11 FG2
e. PSI = 58 + 0.25 T - 2.64 FG2 + 0.79 L
f. PSI = 44 + 0.12 T - 0.18 FG2 + 5.74 KD
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 33. Linear regression plots of unconfined compressive strength versus curing time: Shelby/FG2 systems.

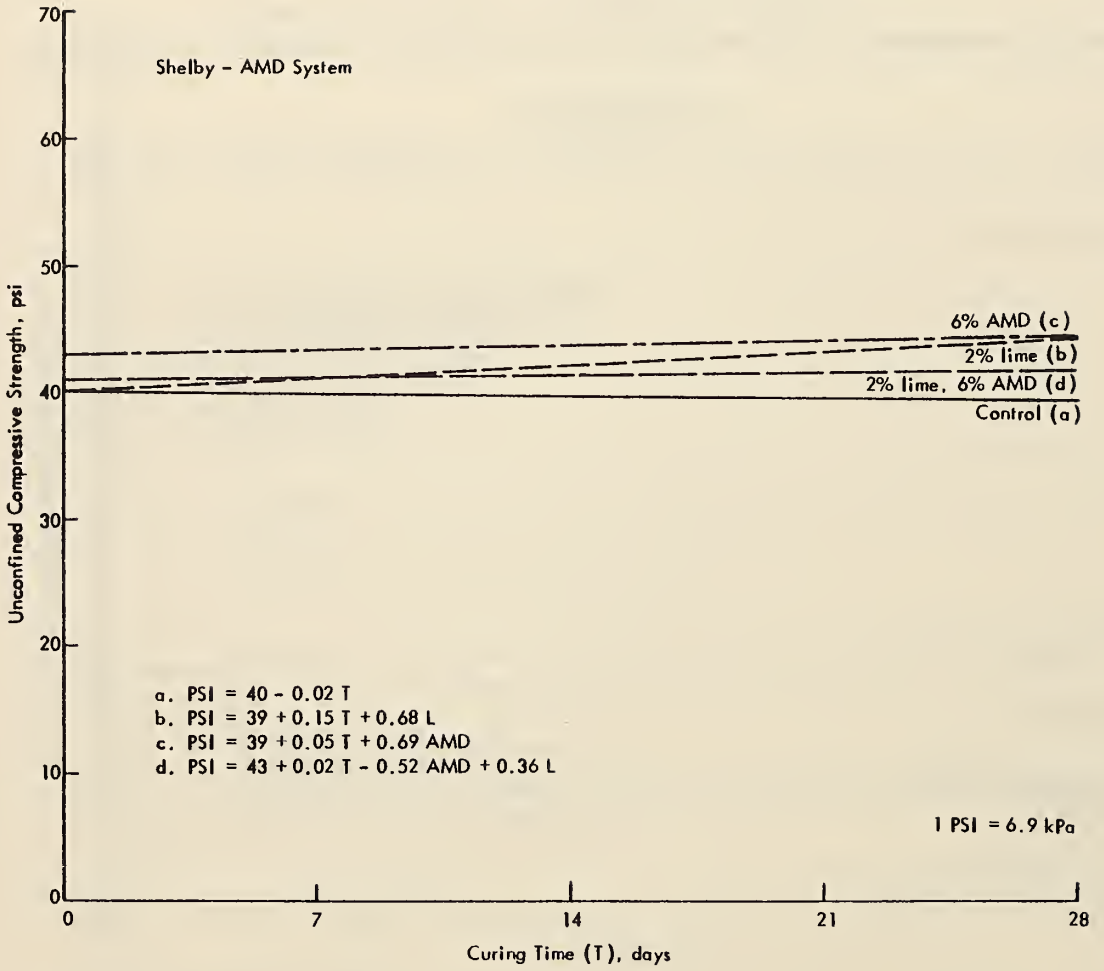

Figure 34. Linear regression plots of unconfined compressive strength versus curing time: Shelby/AMD system.

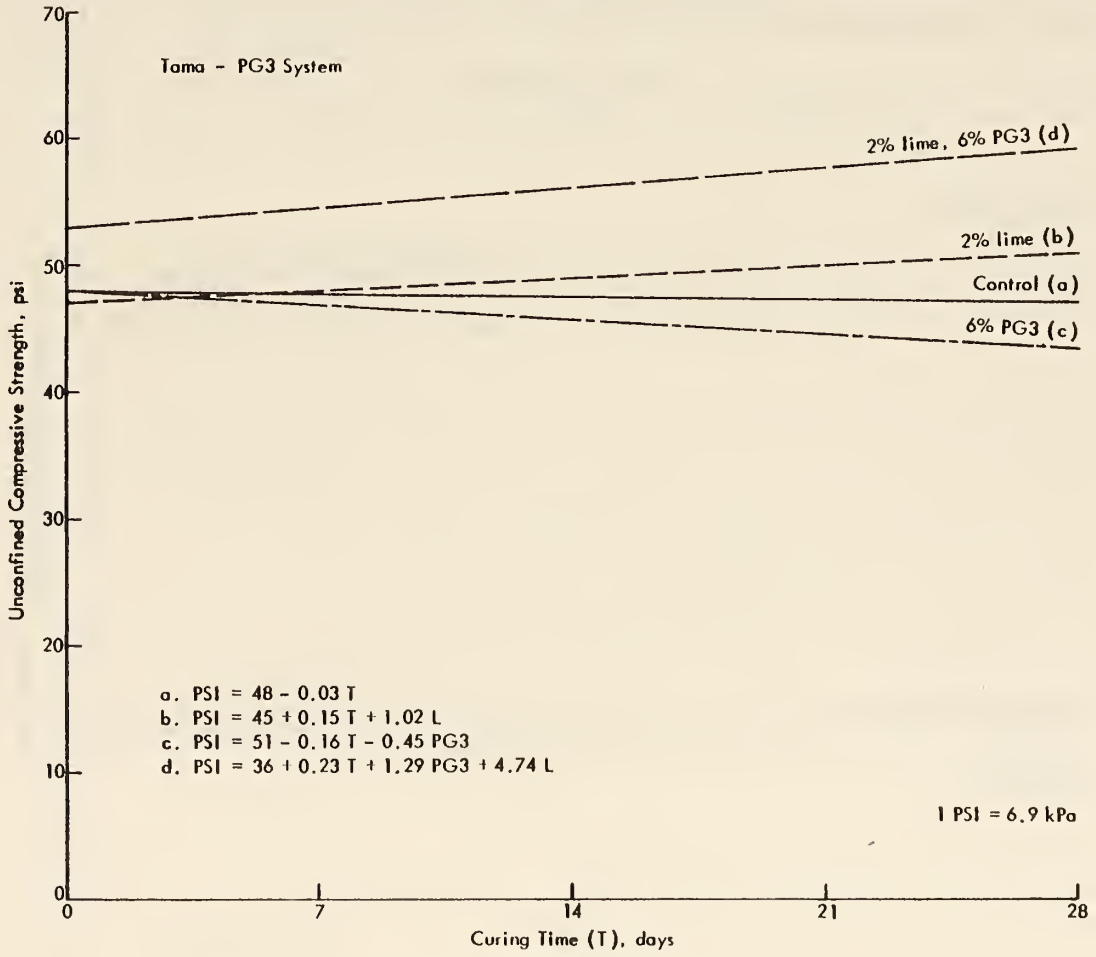

Figure 35. Linear regression plots of unconfined compressive strength versus curing time: Tama/PG3 system.

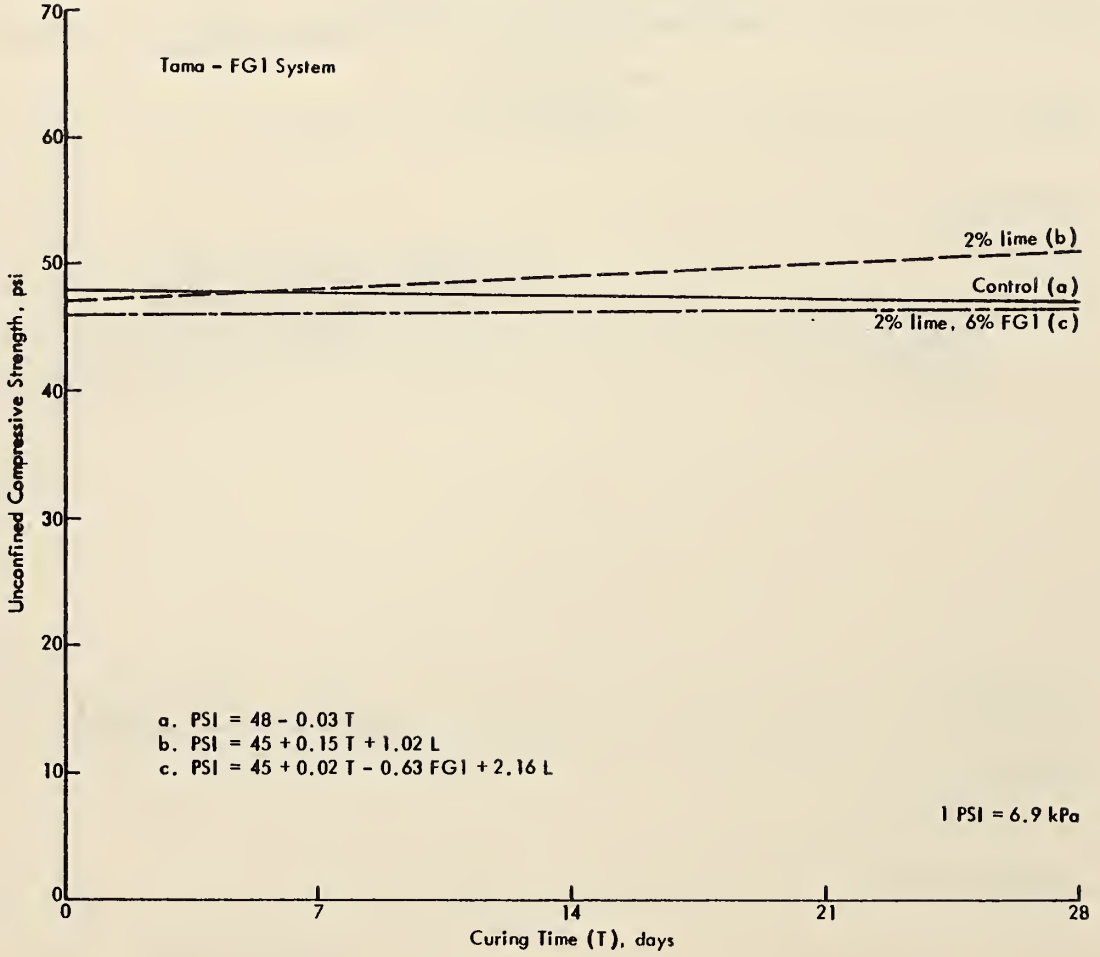

Figure 36. Linear regression plots of unconfined compressive strength versus curing time: Tama/FG1 system.

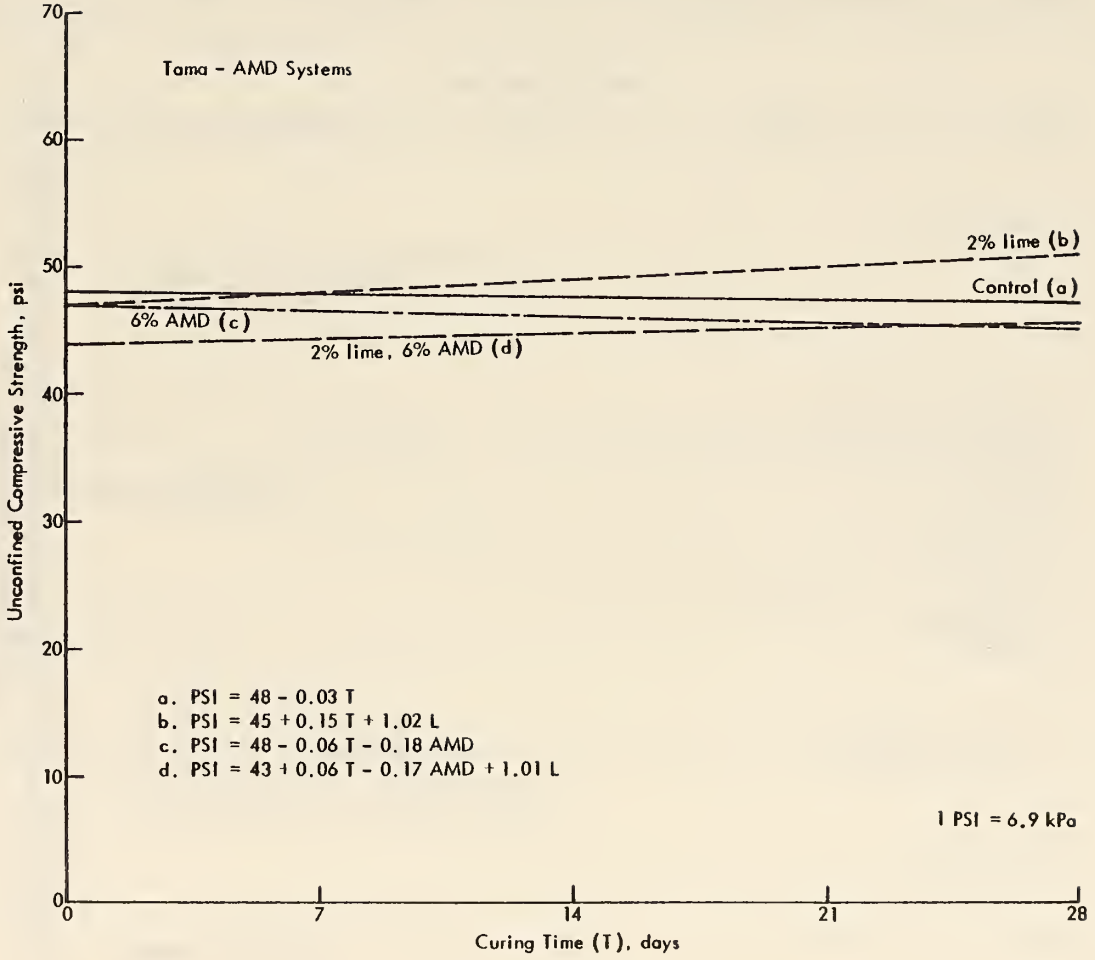

Figure 37. Linear regression plots of unconfined compressive strength versus curing time: Tama/AMD systems.

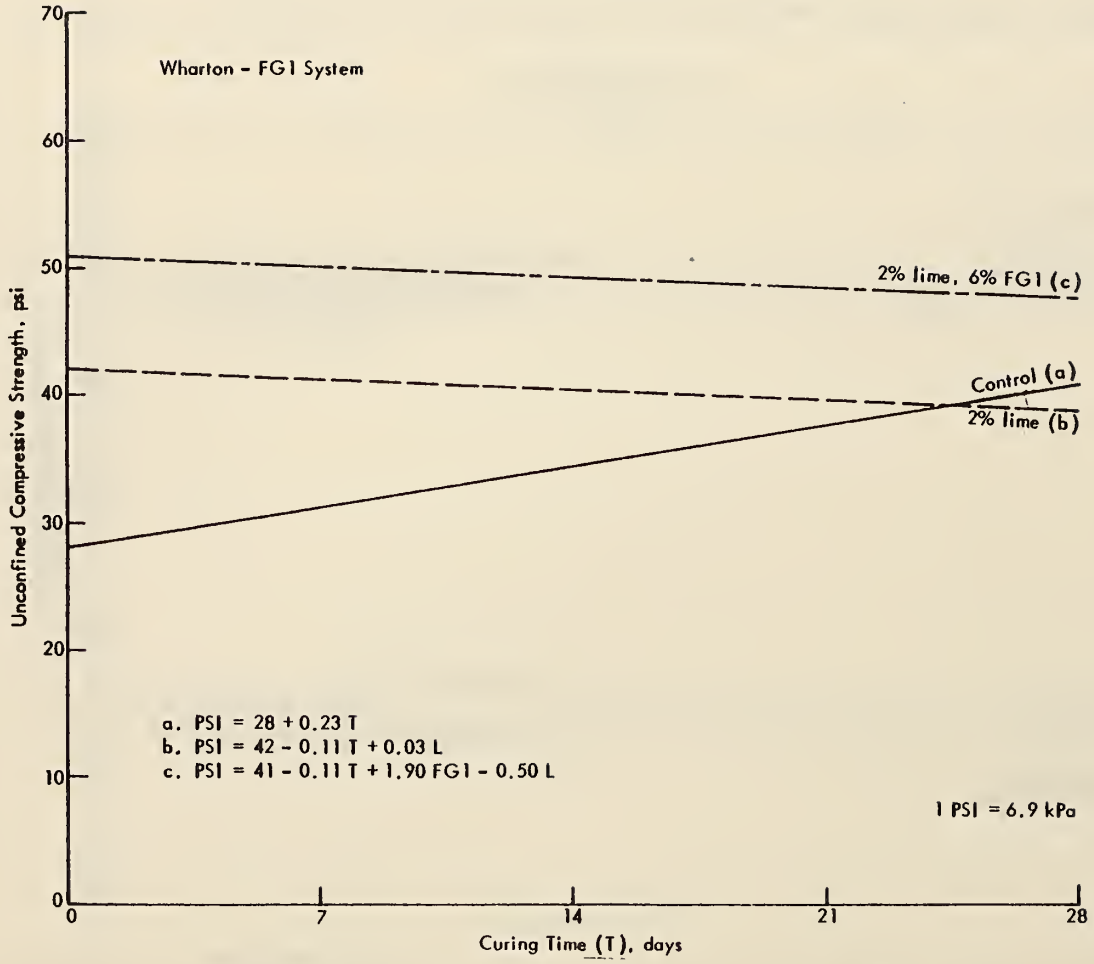

Figure 38. Linear regression plots of unconfined compressive strength versus curing time: Wharton/FG1 system.

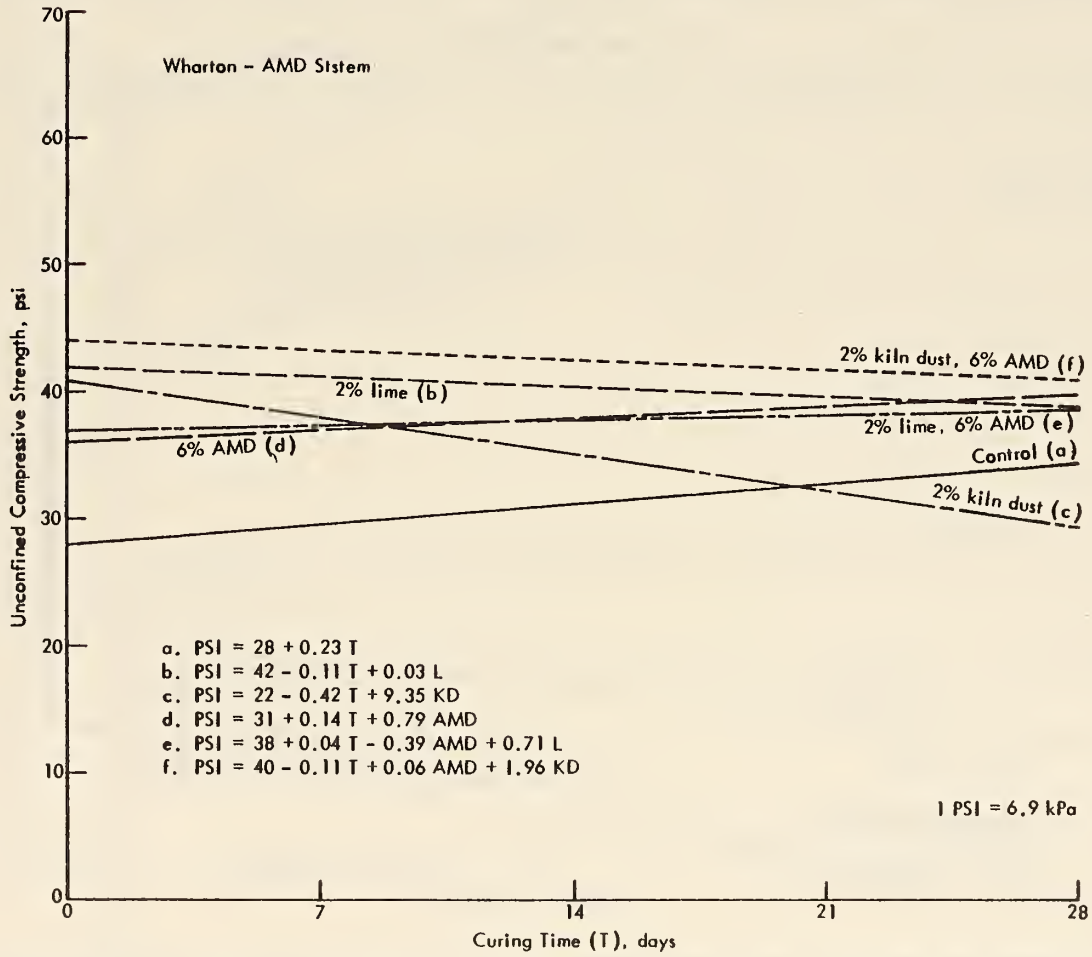
Wharton - AMD Ststem
Unconfined Compressive Strength, psi
Curing Time (T), days
2% kiln dust, 6% AMD (f)
2% lime (b)
2% lime, 6% AMD (e)
6% AMD (d)
Control (a)
2% kiln dust (c)
a. PSI = 28 + 0.23 T
b. PSI = 42 - 0.11 T + 0.03 L
c. PSI = 22 - 0.42 T + 9.35 KD
d. PSI = 31 + 0.14 T + 0.79 AMD
e. PSI = 38 + 0.04 T - 0.39 AMD + 0.71 L
f. PSI = 40 - 0.11 T + 0.06 AMD + 1.96 KD
1 PSI = 6.9 kPa
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 39. Linear regression plots of unconfined compressive strength versus curing time: Wharton/AMD system.

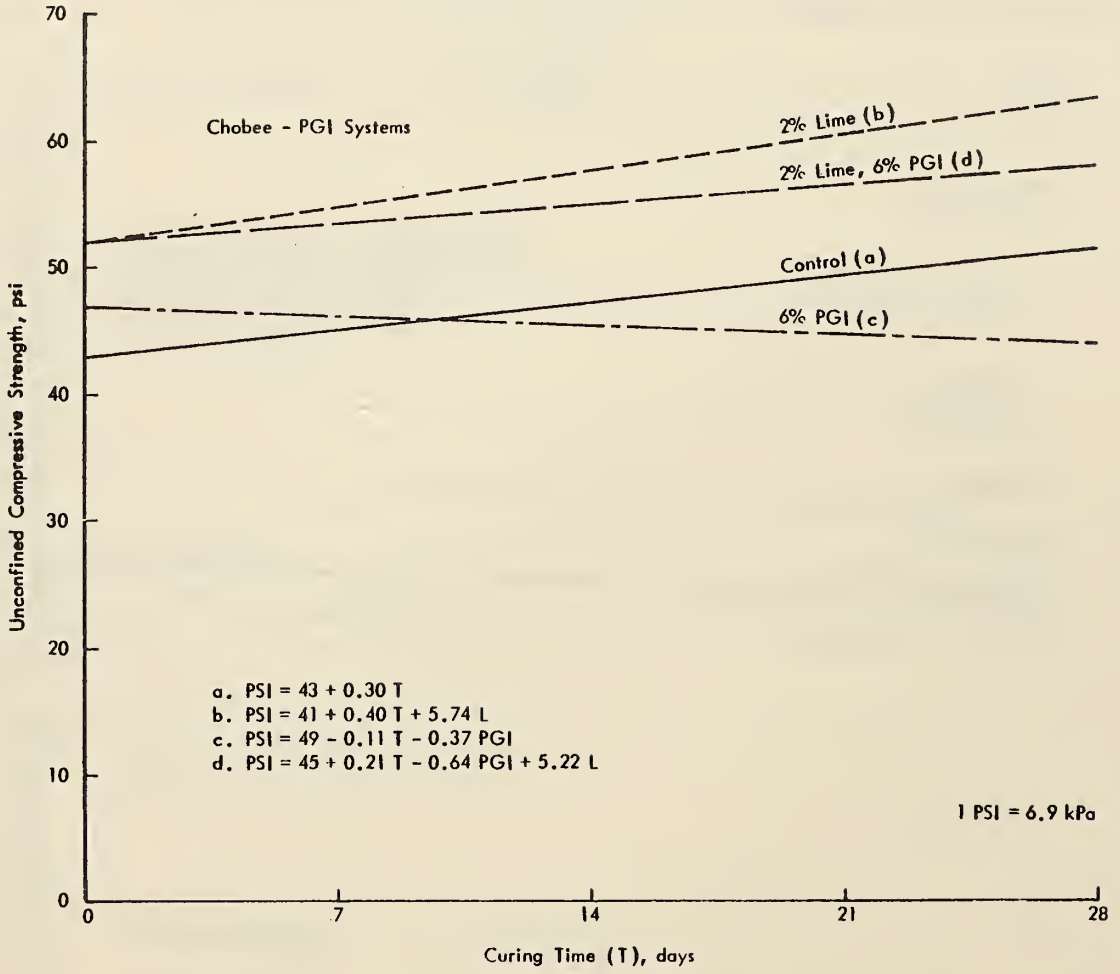

Figure 40. Linear regression plots of unconfined compressive strength versus curing time: Chobee/PGI systems.

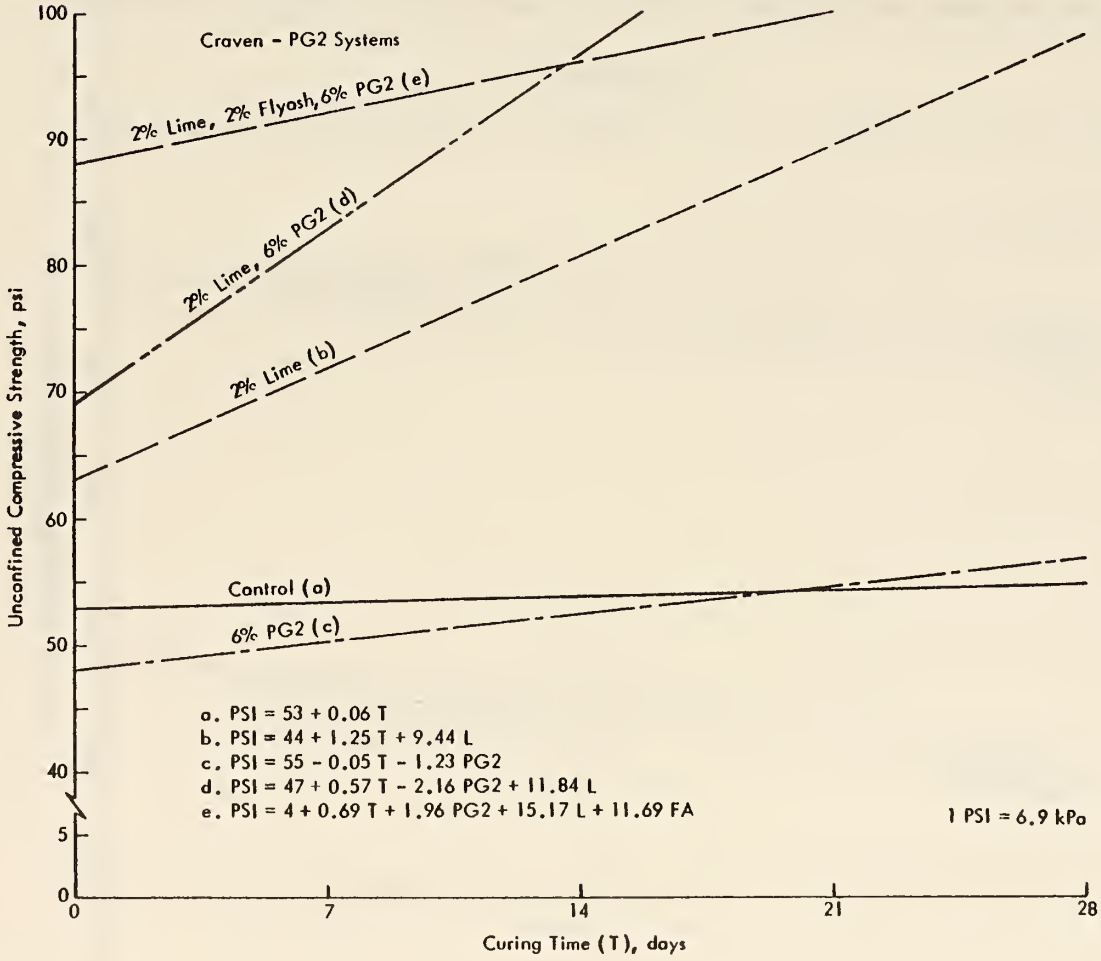

Figure 41. Linear regression plots of unconfined compressive strength versus curing time: Craven/PG2 systems.

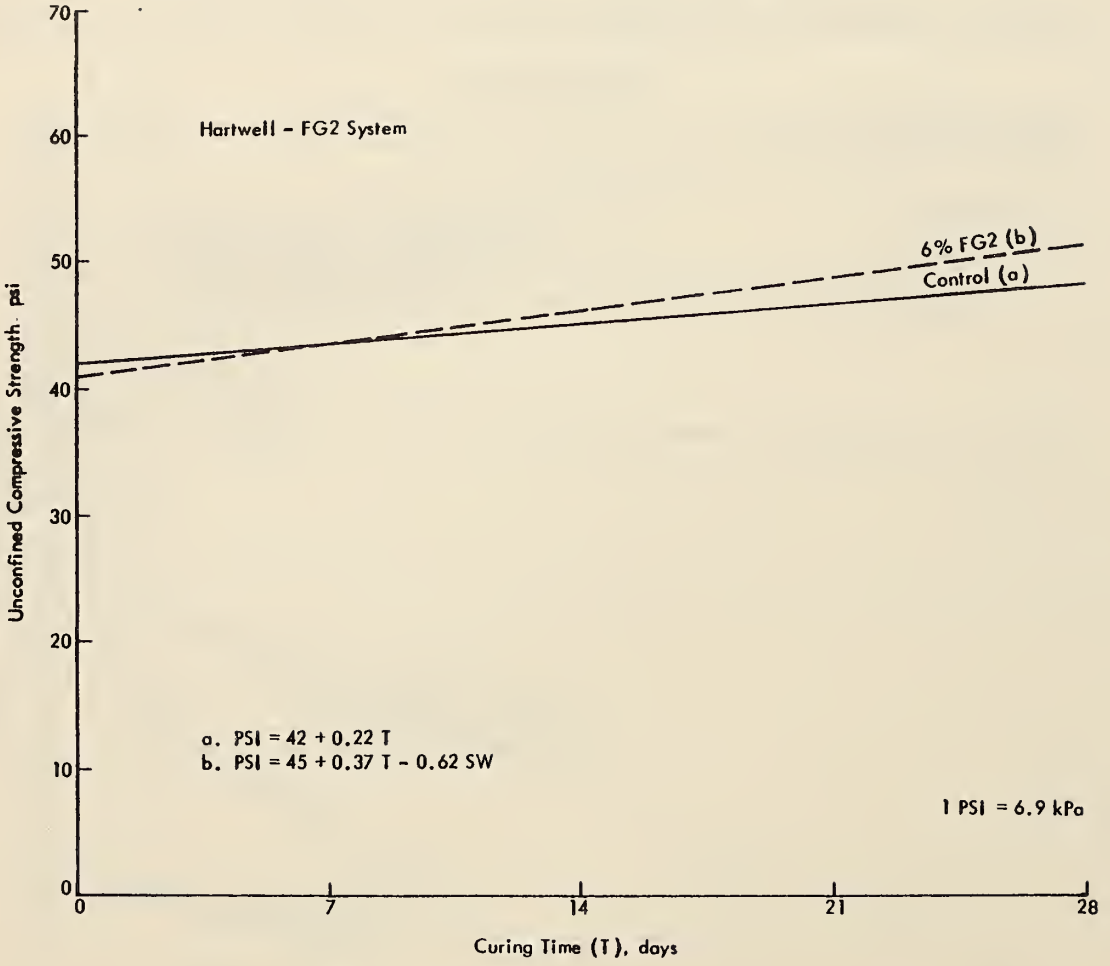

Figure 42. Linear regression plots of unconfined compressive strength versus curing time: Hartwell/FG2 system.

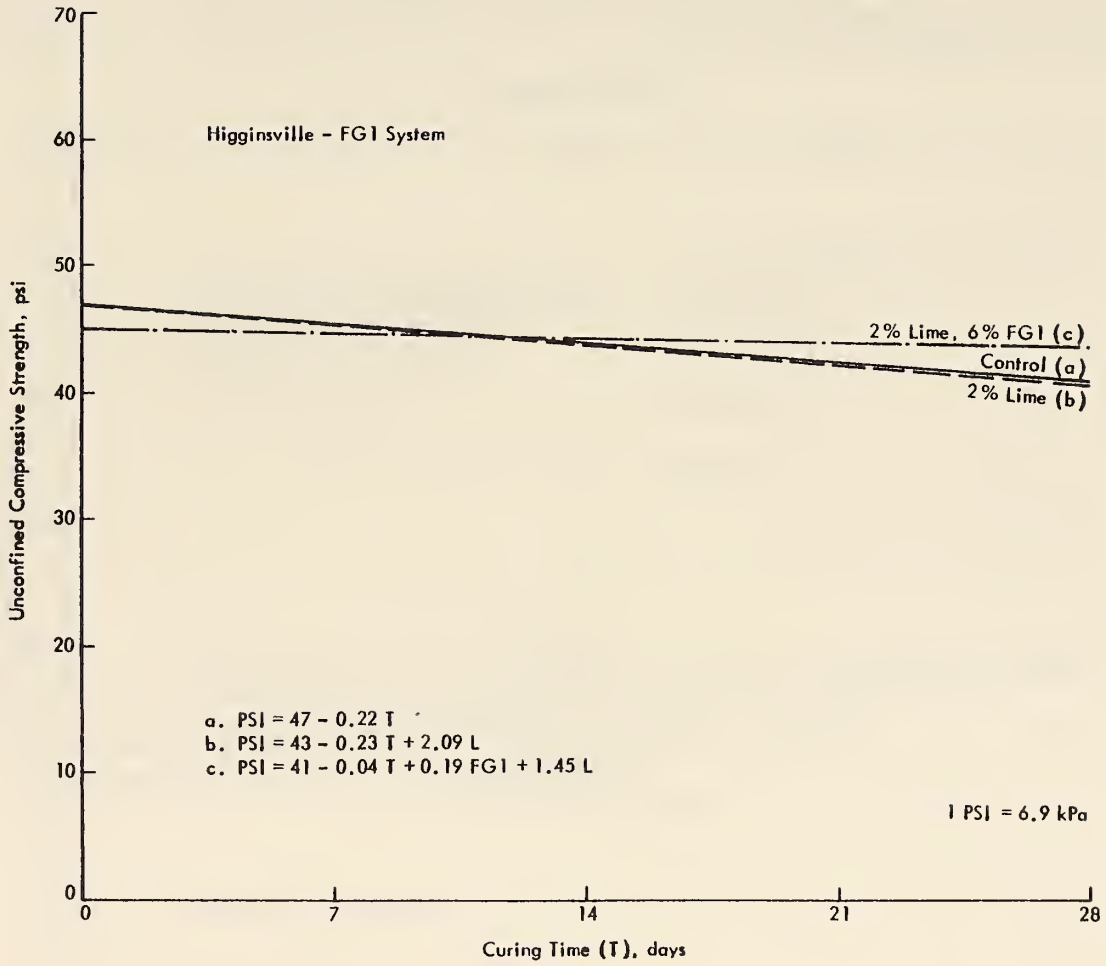

Figure 43. Linear regression plots of unconfined compressive strength versus curing time: Higginsville/FG1 system.

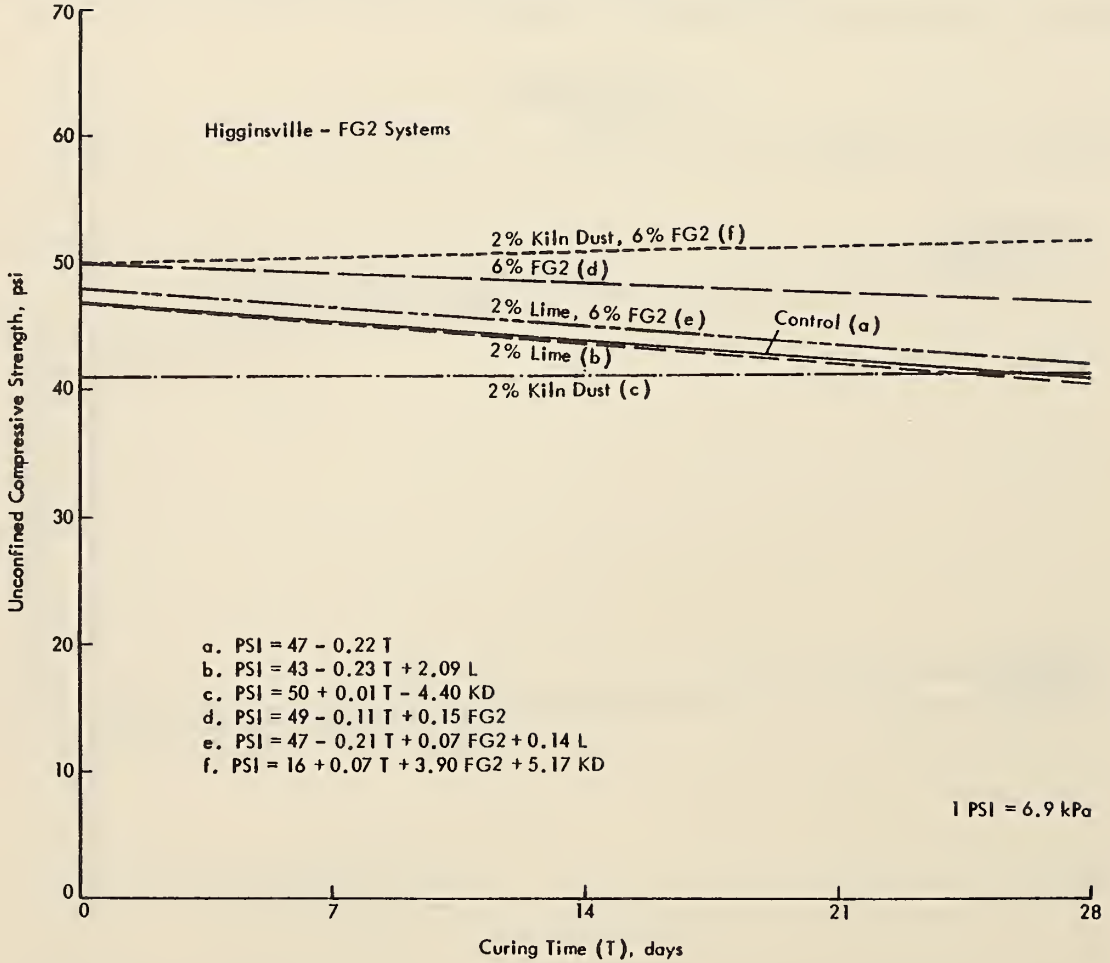
Higginsville - FG2 Systems
2% Kiln Dust, 6% FG2 (f)
6% FG2 (d)
2% Lime, 6% FG2 (e)
Control (a)
2% Lime (b)
2% Kiln Dust (c)
a. PSI = 47 - 0.22 T
b. PSI = 43 - 0.23 T + 2.09 L
c. PSI = 50 + 0.01 T - 4.40 KD
d. PSI = 49 - 0.11 T + 0.15 FG2
e. PSI = 47 - 0.21 T + 0.07 FG2 + 0.14 L
f. PSI = 16 + 0.07 T + 3.90 FG2 + 5.17 KD
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 44. Linear regression plots of unconfined compressive strength versus curing time: Higginsville/FG2 systems.

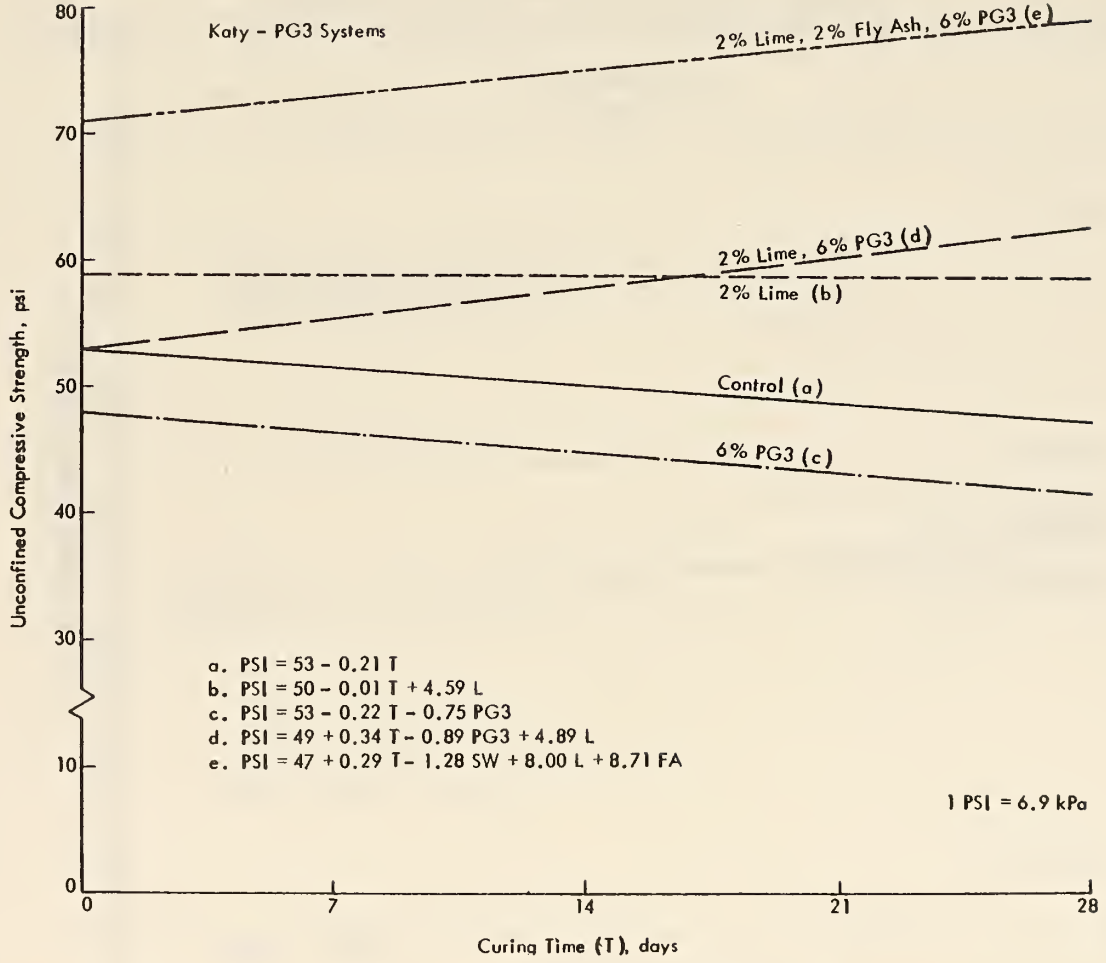
Katy - PG3 Systems
2% Lime, 2% Fly Ash, 6% PG3 (e)
2% Lime, 6% PG3 (d)
2% Lime (b)
Control (a)
6% PG3 (c)
a. PSI = 53 - 0.21 T
b. PSI = 50 - 0.01 T + 4.59 L
c. PSI = 53 - 0.22 T - 0.75 PG3
d. PSI = 49 + 0.34 T - 0.89 PG3 + 4.89 L
e. PSI = 47 + 0.29 T - 1.28 SW + 8.00 L + 8.71 FA
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
30
40
50
60
70
80
0
7
14
21
28

Figure 45. Linear regression plots of unconfined compressive strength versus curing time: Katy/PG3 systems.

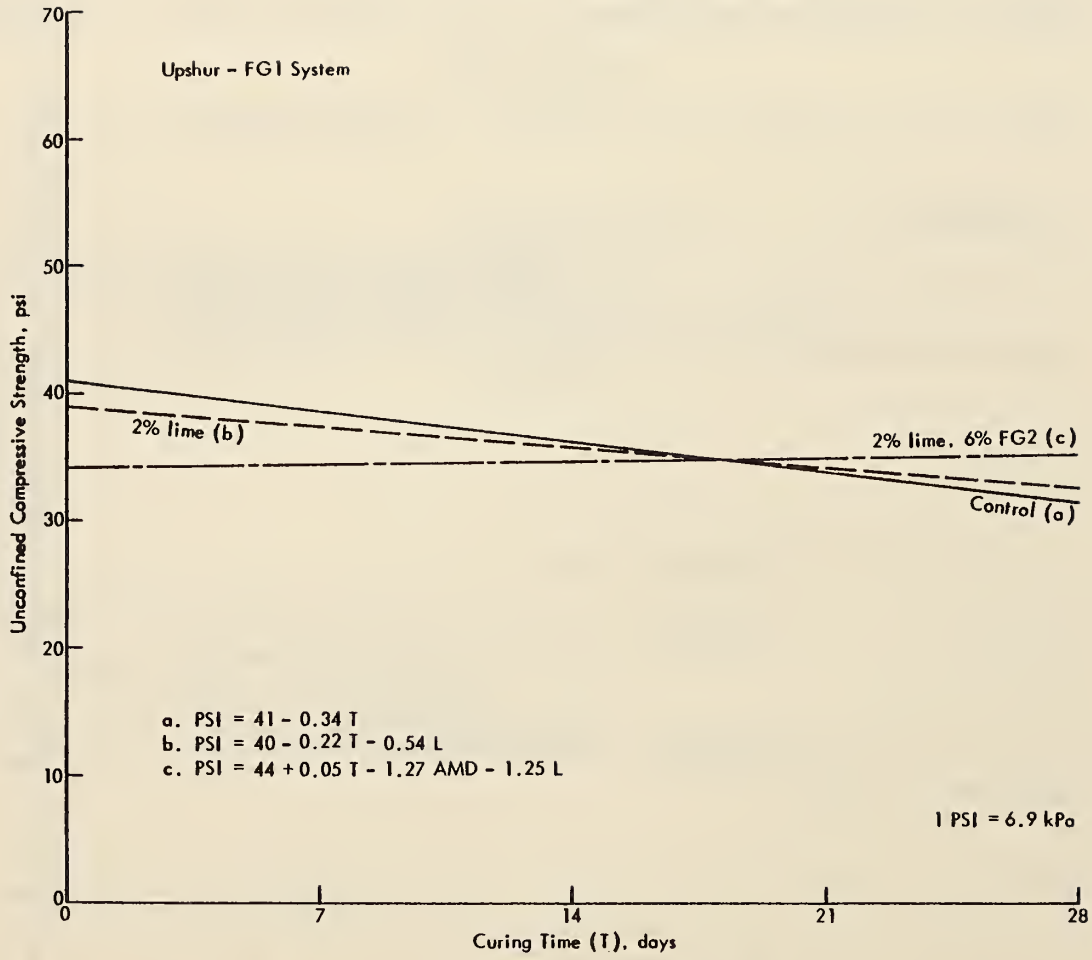

Figure 46. Linear regression plots of unconfined compressive strength versus curing time: Upshur/FG1 system.

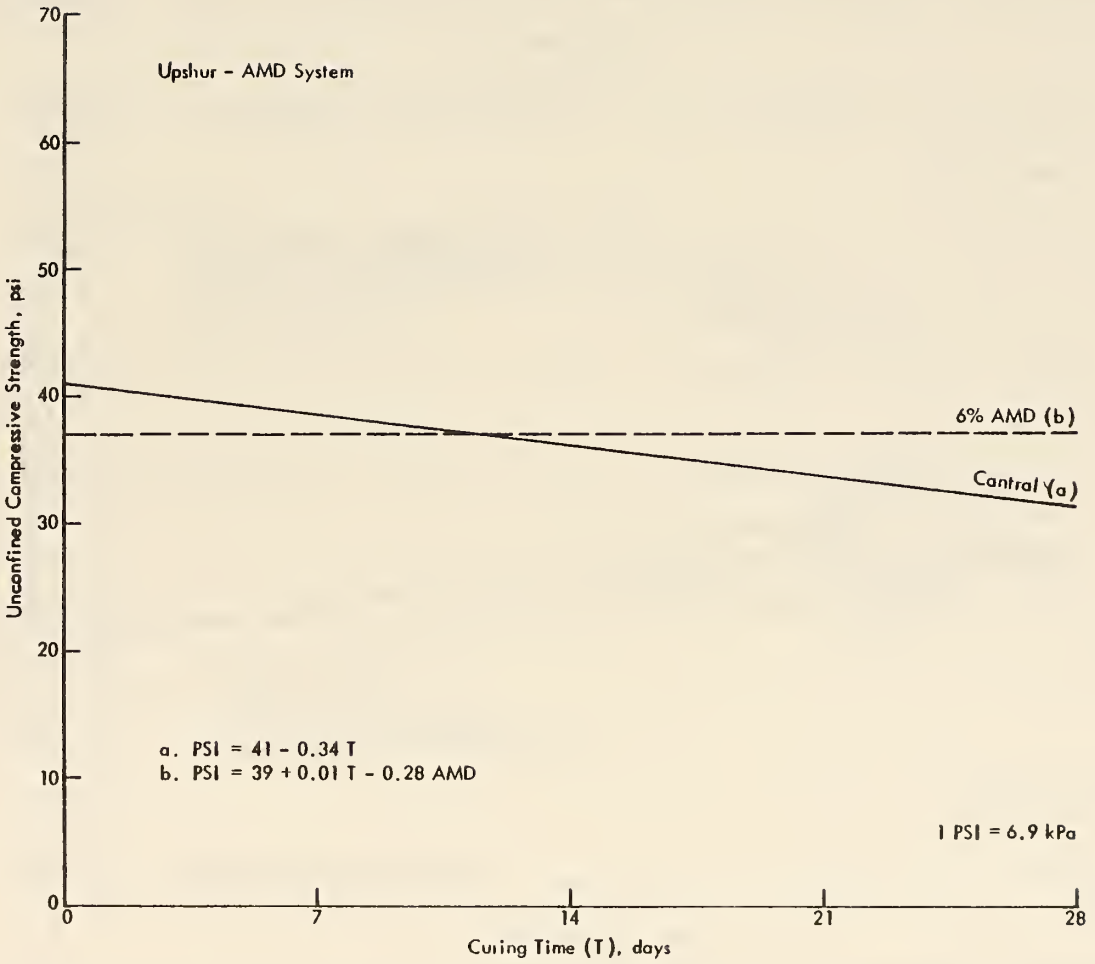

Figure 47. Linear regression plots of unconfined compressive strength versus curing time: Upshur/AMD system.

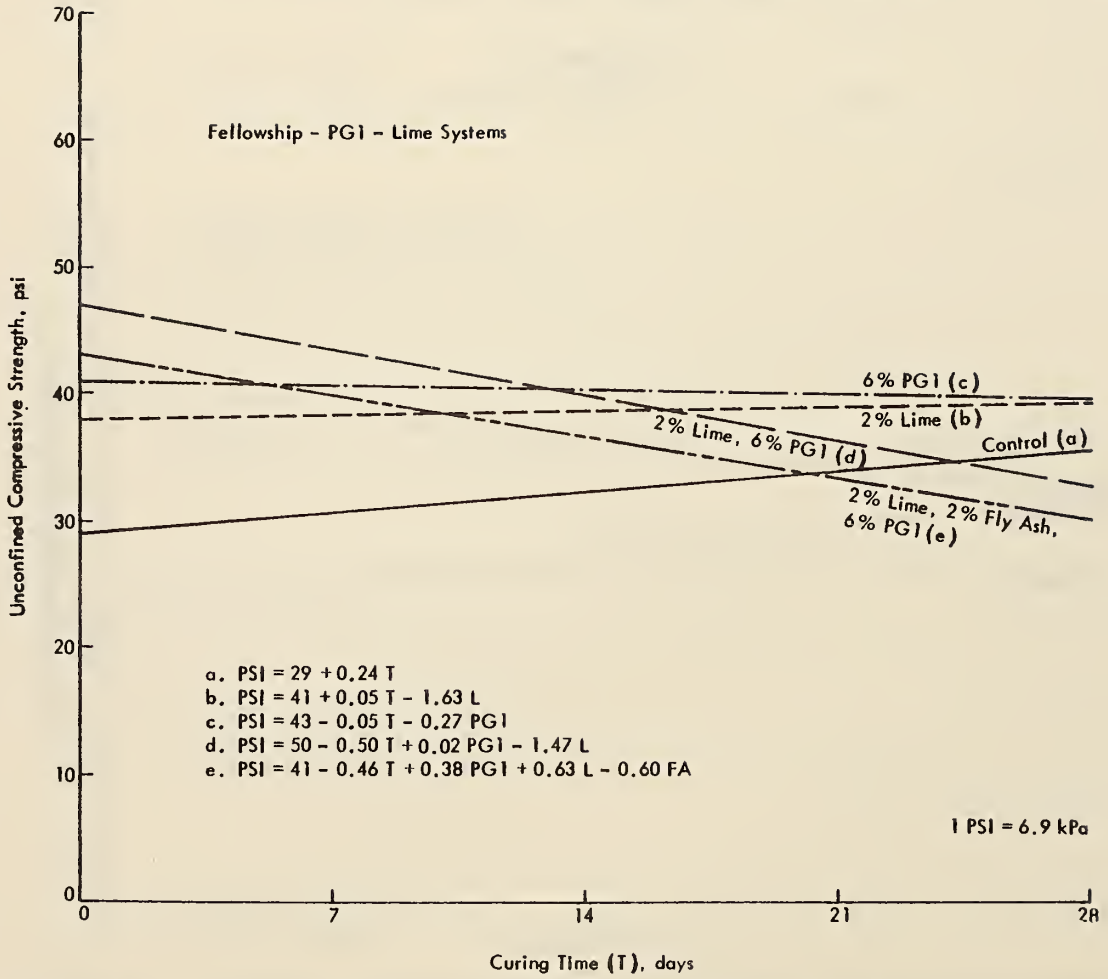
Fellowship - PG1 - Lime Systems
Unconfined Compressive Strength, psi
Curing Time (T), days
70
60
50
40
30
20
10
0
0
7
14
21
28
6% PG1 (c)
2% Lime (b)
2% Lime, 6% PG1 (d)
Control (a)
2% Lime, 2% Fly Ash, 6% PG1 (e)
a. PSI = 29 + 0.24 T
b. PSI = 41 + 0.05 T - 1.63 L
c. PSI = 43 - 0.05 T - 0.27 PG1
d. PSI = 50 - 0.50 T + 0.02 PG1 - 1.47 L
e. PSI = 41 - 0.46 T + 0.38 PG1 + 0.63 L - 0.60 FA
1 PSI = 6.9 kPa

Figure 48. Linear regression plots of unconfined compressive strength versus curing time: Fellowship/PG1/Lime systems.

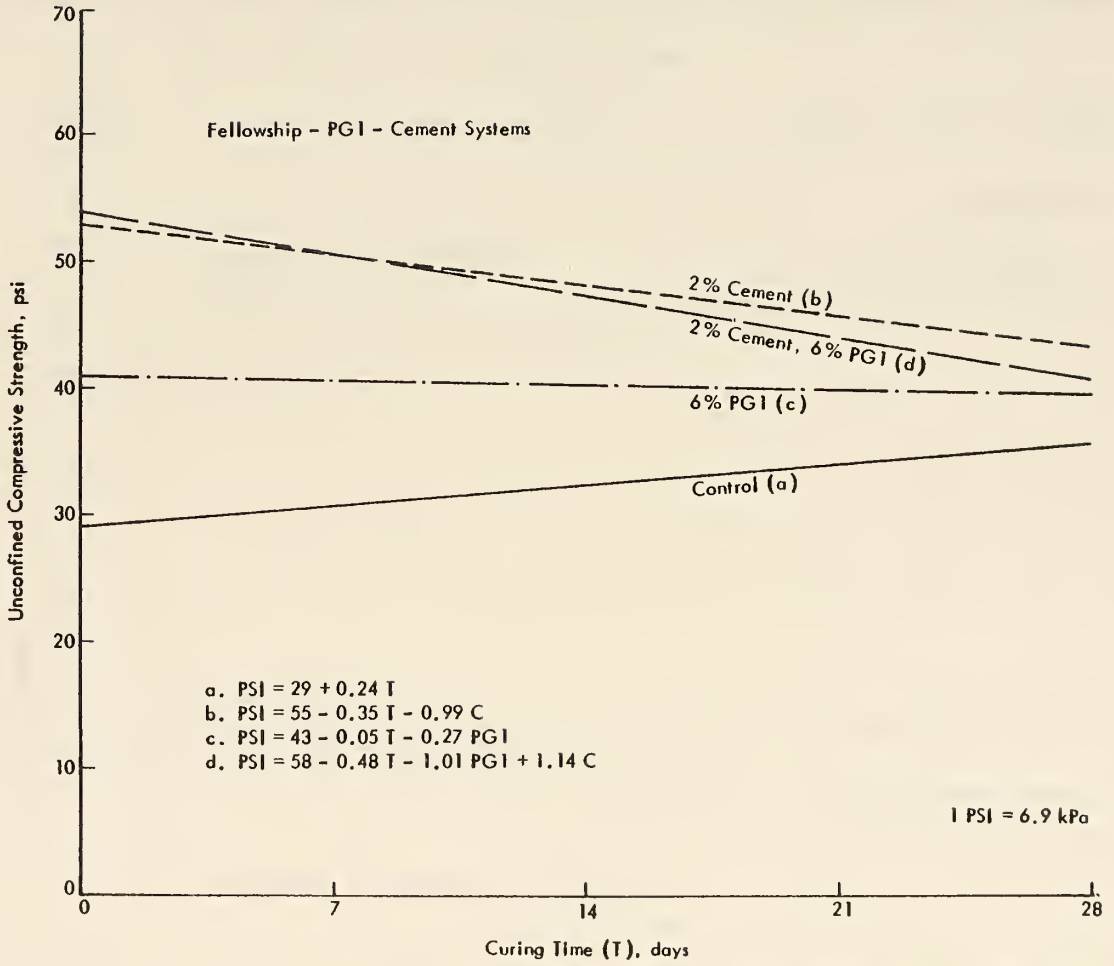

Figure 49. Linear regression plots of unconfined compressive strength versus curing time: Fellowship/PGI/Cement systems.

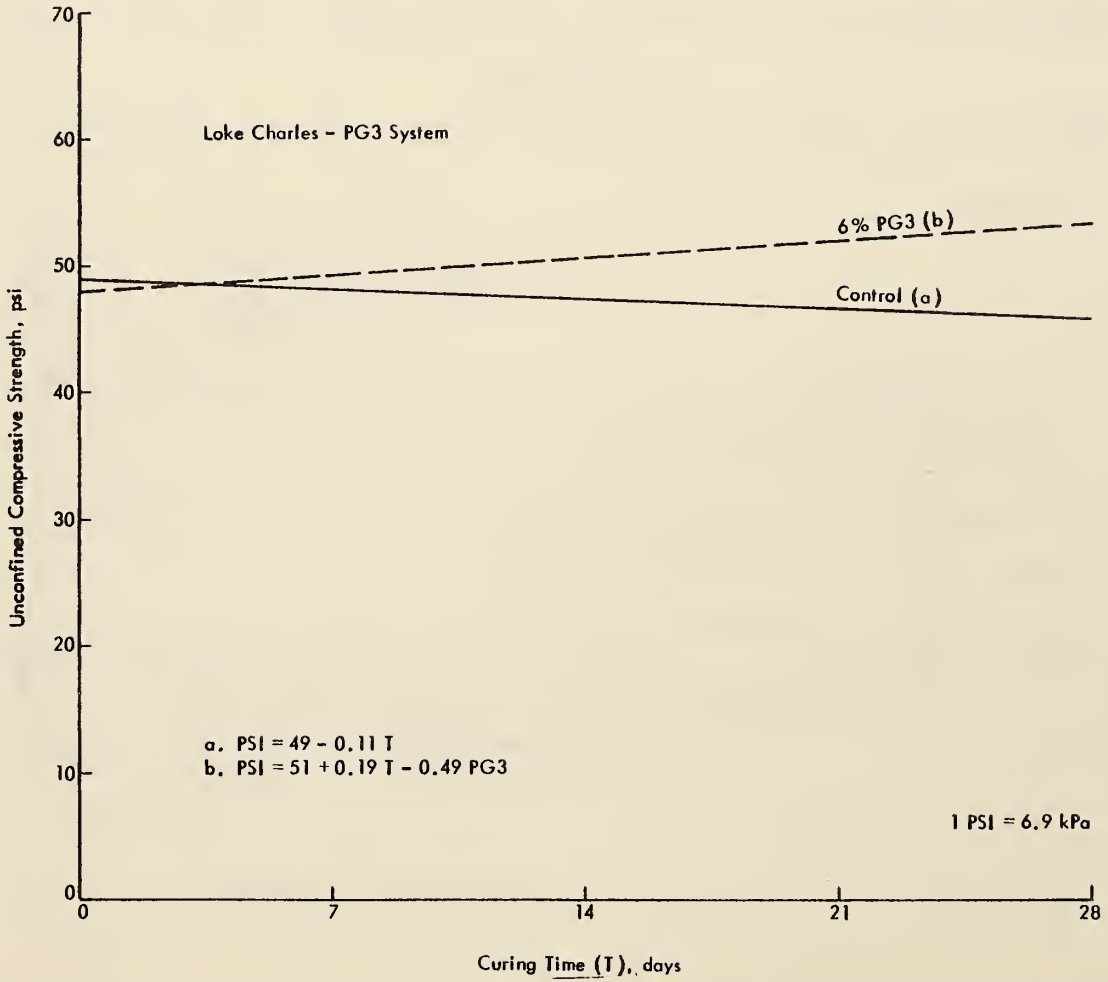

Figure 50. Linear regression plots of unconfined compressive strength versus curing time: Lake Charles/PG3 system.

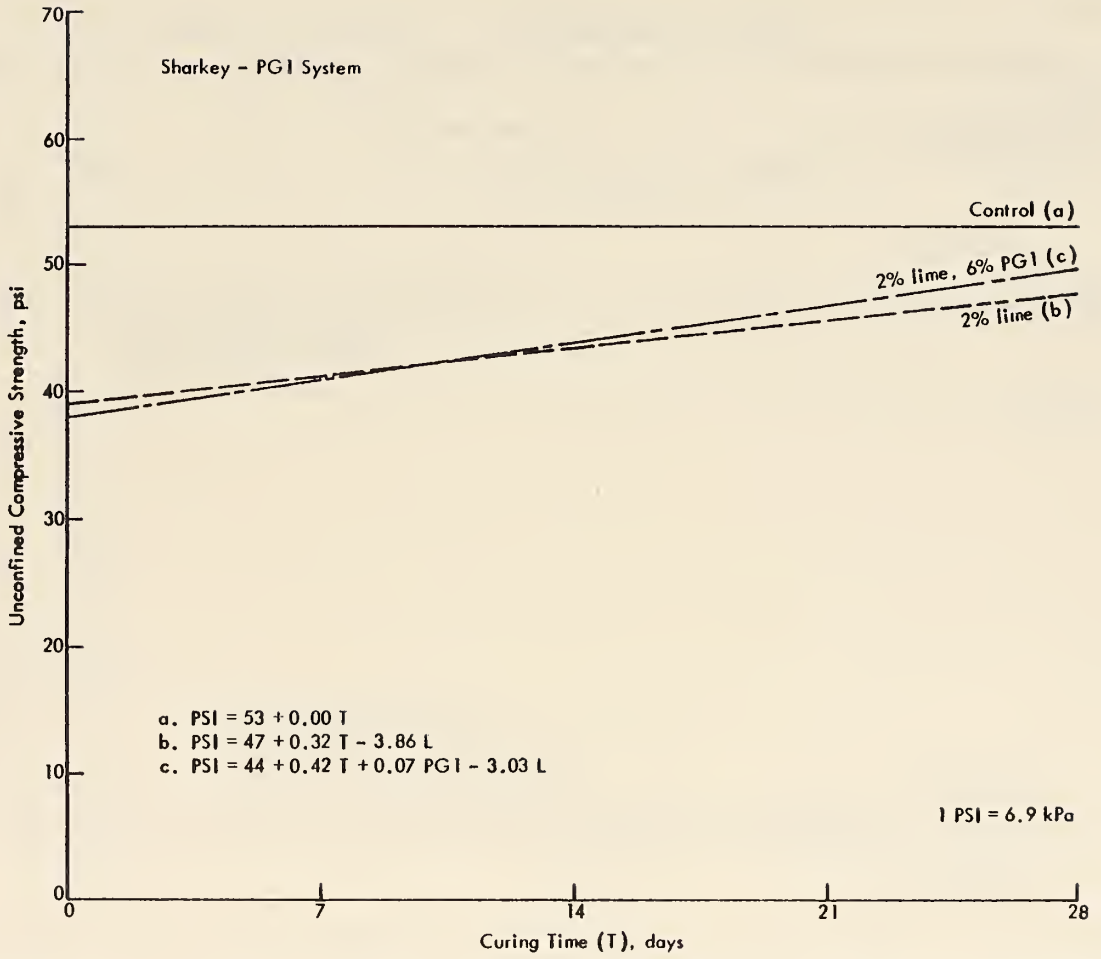

Figure 51. Linear regression plots of unconfined compressive strength versus curing time: Sharkey/PG1 system.

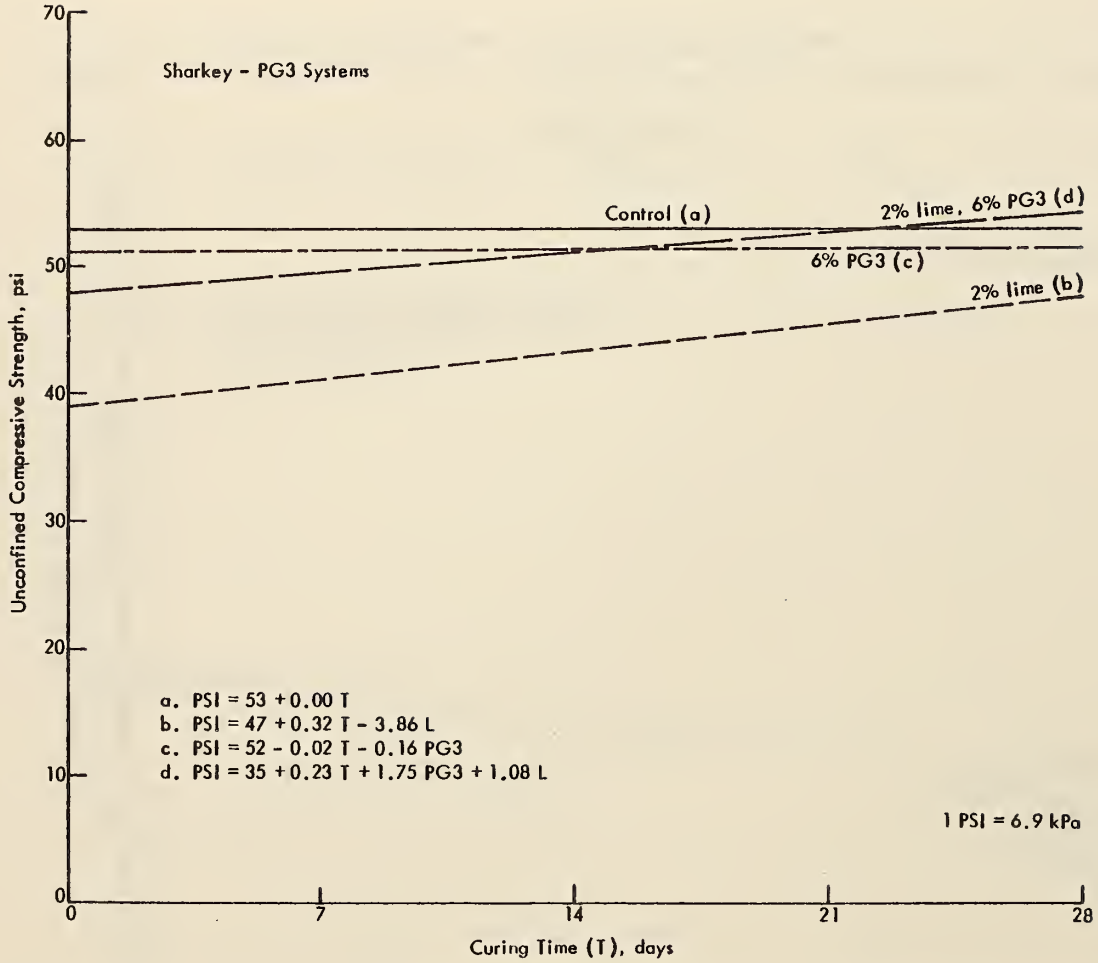

Figure 52. Linear regression plots of unconfined compressive strength versus curing time: Sharkey/PG3 systems.

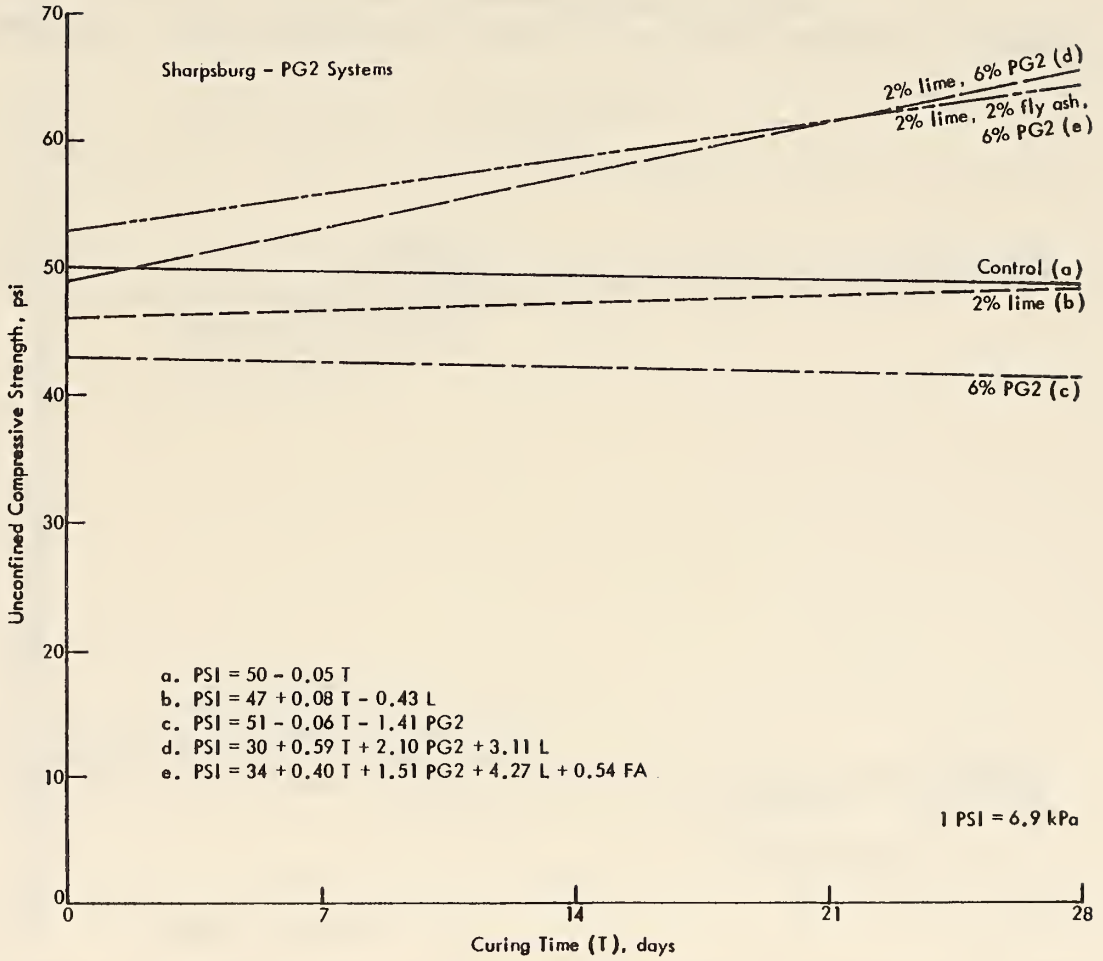
Sharpsburg - PG2 Systems
2% lime, 6% PG2 (d)
2% lime, 2% fly ash, 6% PG2 (e)
Control (a)
2% lime (b)
6% PG2 (c)
a. PSI = 50 - 0.05 T
b. PSI = 47 + 0.08 T - 0.43 L
c. PSI = 51 - 0.06 T - 1.41 PG2
d. PSI = 30 + 0.59 T + 2.10 PG2 + 3.11 L
e. PSI = 34 + 0.40 T + 1.51 PG2 + 4.27 L + 0.54 FA
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 53. Linear regression plots of unconfined compressive strength versus curing time: Sharpsburg/PG2 systems.

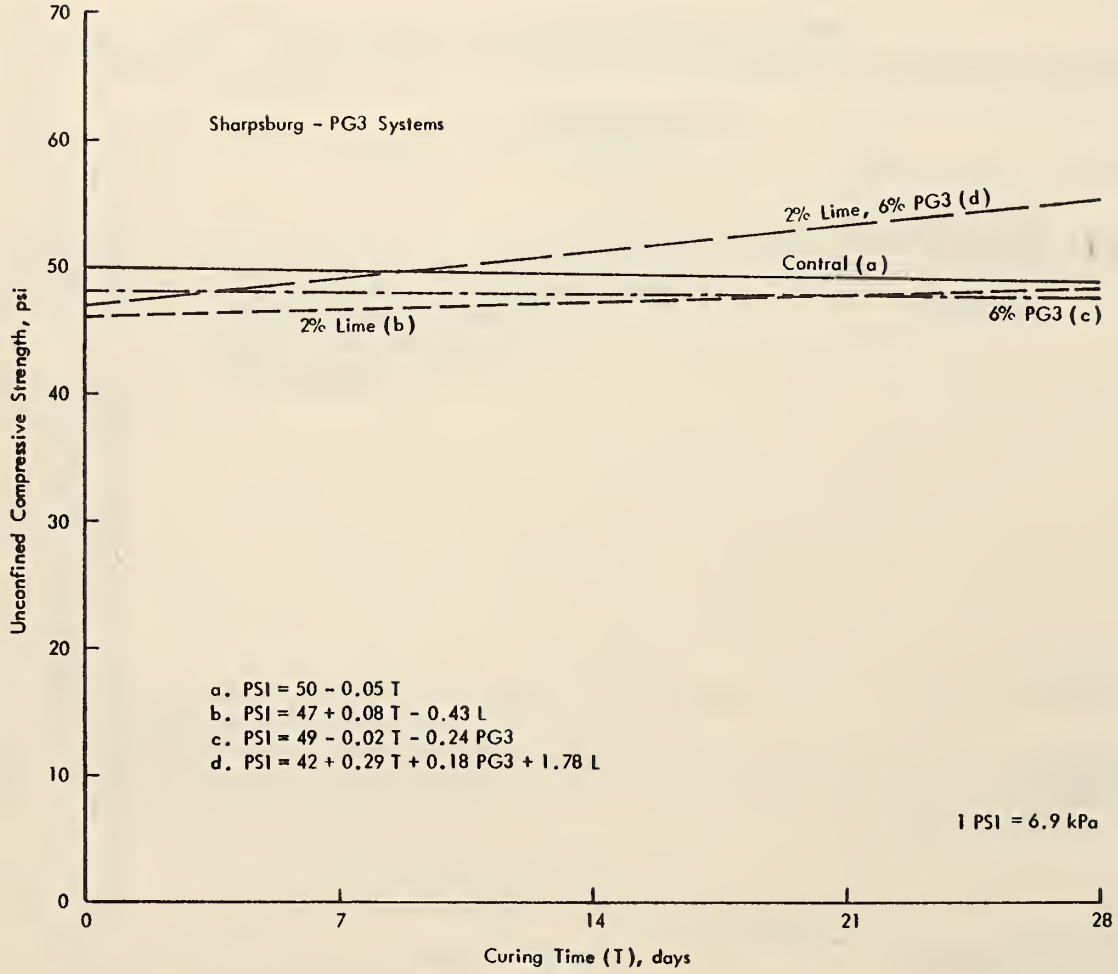

Figure 54. Linear regression plots of unconfined compressive strength versus curing time: Sharpsburg/PG3 systems.

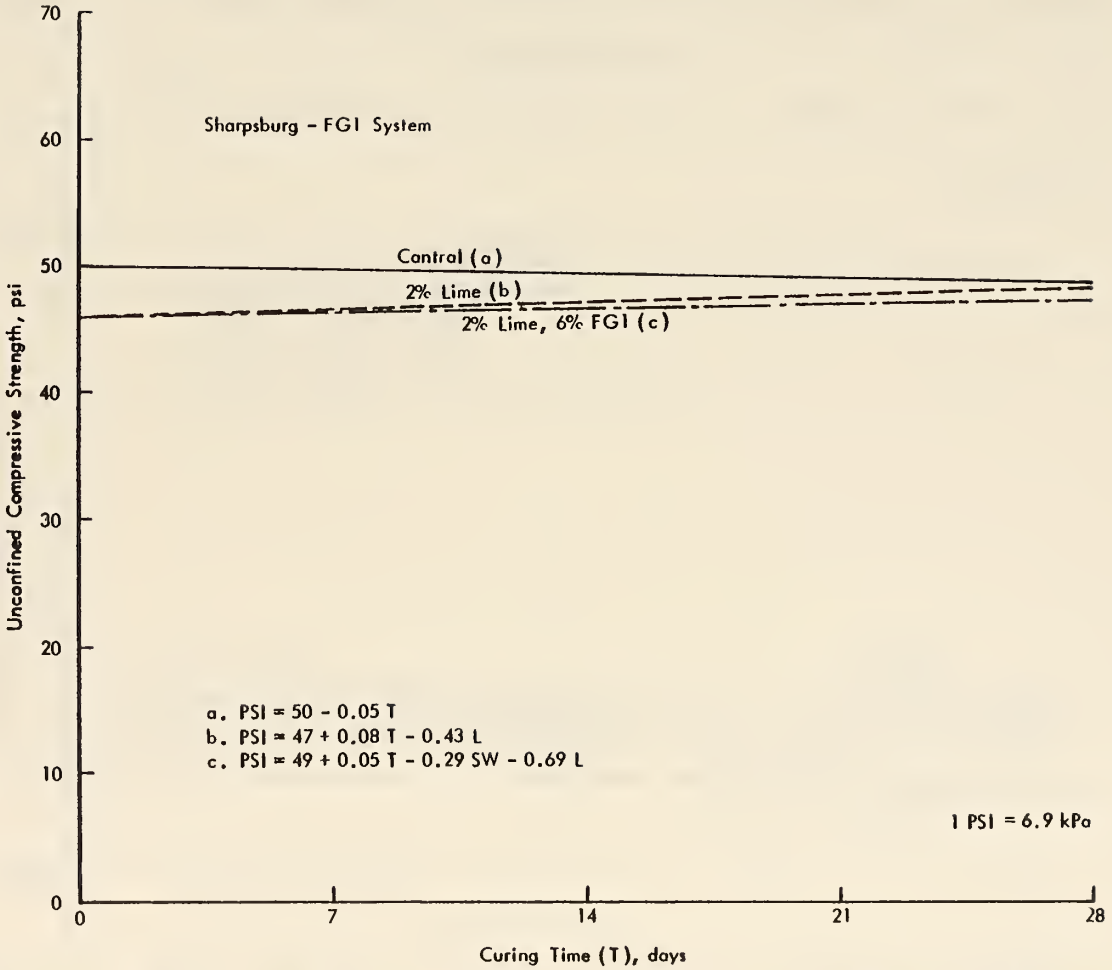

Figure 55. Linear regression plots of unconfined compressive strength versus curing time: Sharpsburg/FG1 system.

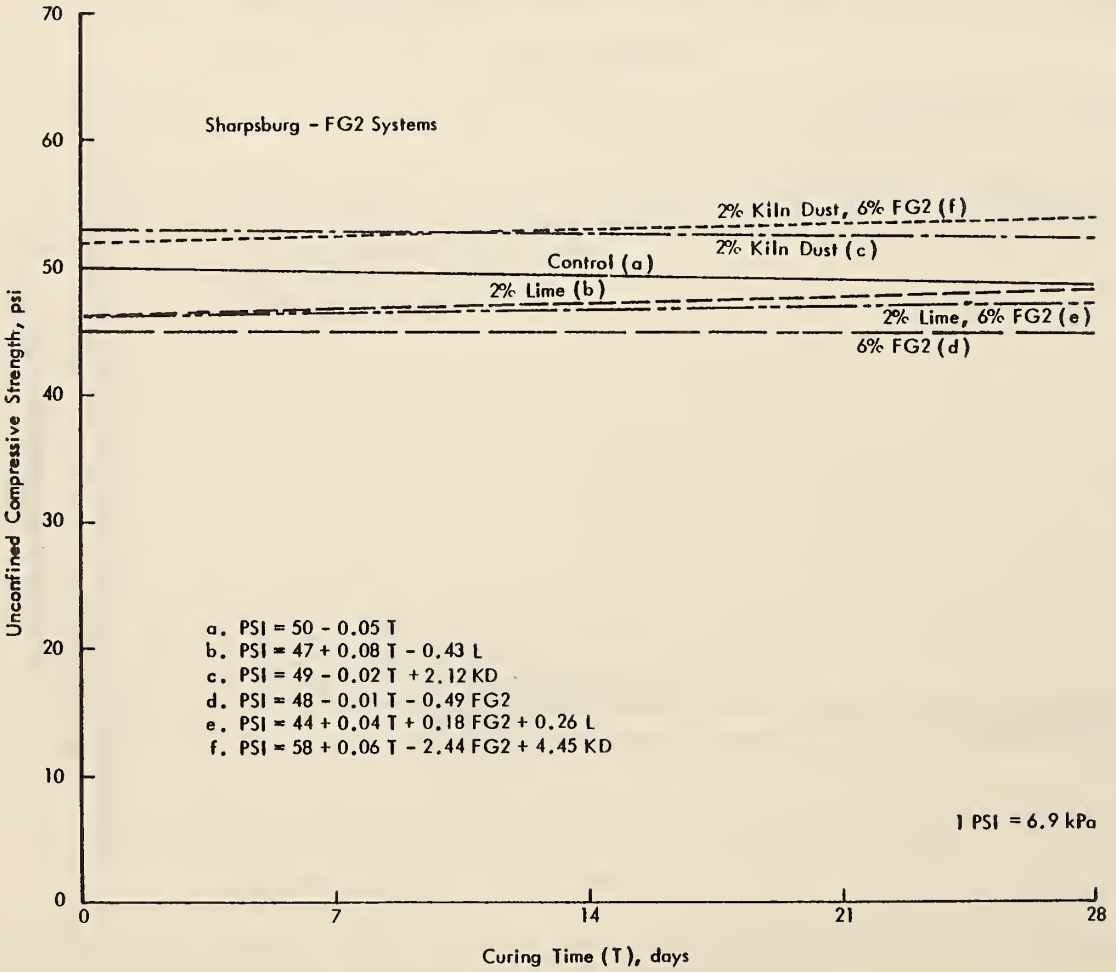
Sharpsburg - FG2 Systems
2% Kiln Dust, 6% FG2 (f)
2% Kiln Dust (c)
Control (a)
2% Lime (b)
2% Lime, 6% FG2 (e)
6% FG2 (d)
a. PSI = 50 - 0.05 T
b. PSI = 47 + 0.08 T - 0.43 L
c. PSI = 49 - 0.02 T + 2.12 KD
d. PSI = 48 - 0.01 T - 0.49 FG2
e. PSI = 44 + 0.04 T + 0.18 FG2 + 0.26 L
f. PSI = 58 + 0.06 T - 2.44 FG2 + 4.45 KD
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 56. Linear regression plots of unconfined compressive strength versus curing time: Sharpsburg/FG2 systems.

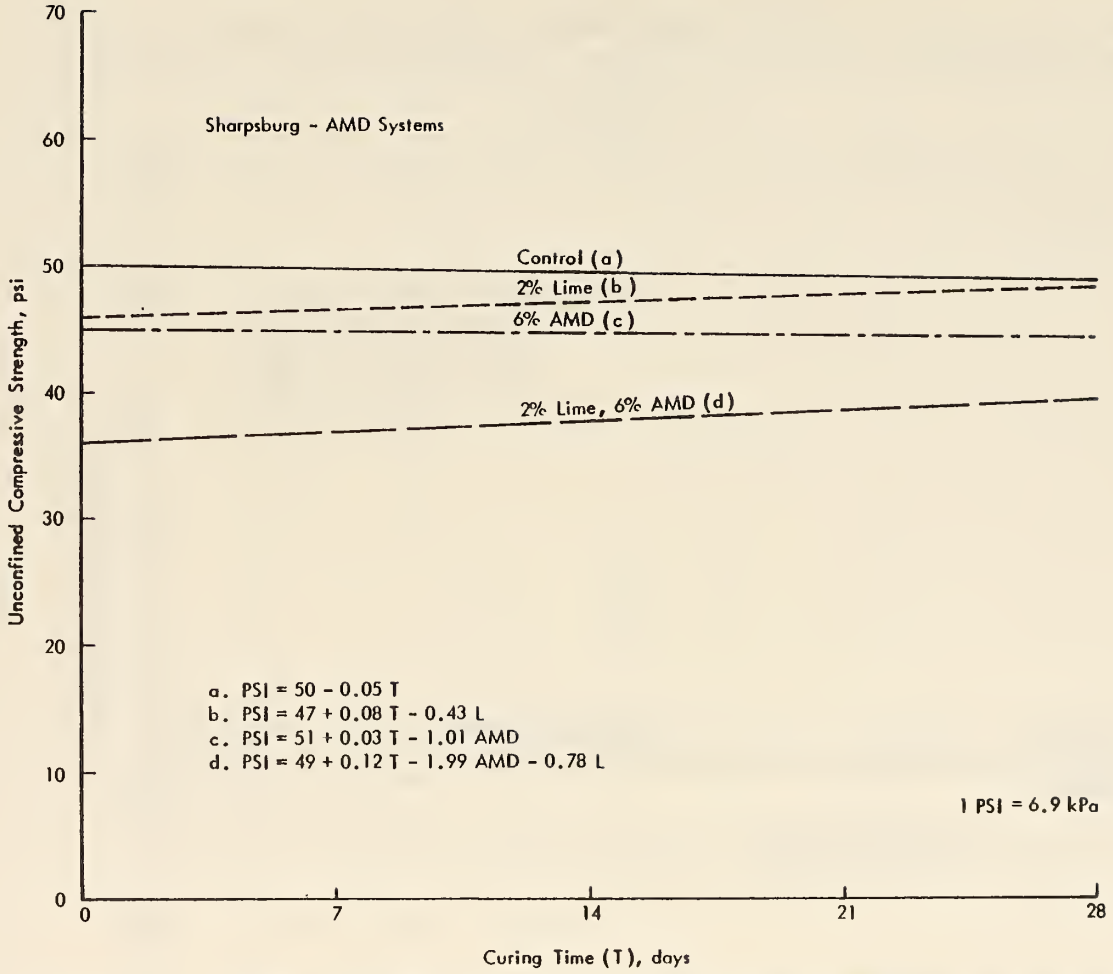

Figure 57. Linear regression plots of unconfined compressive strength versus curing time: Sharpsburg/AMD systems.

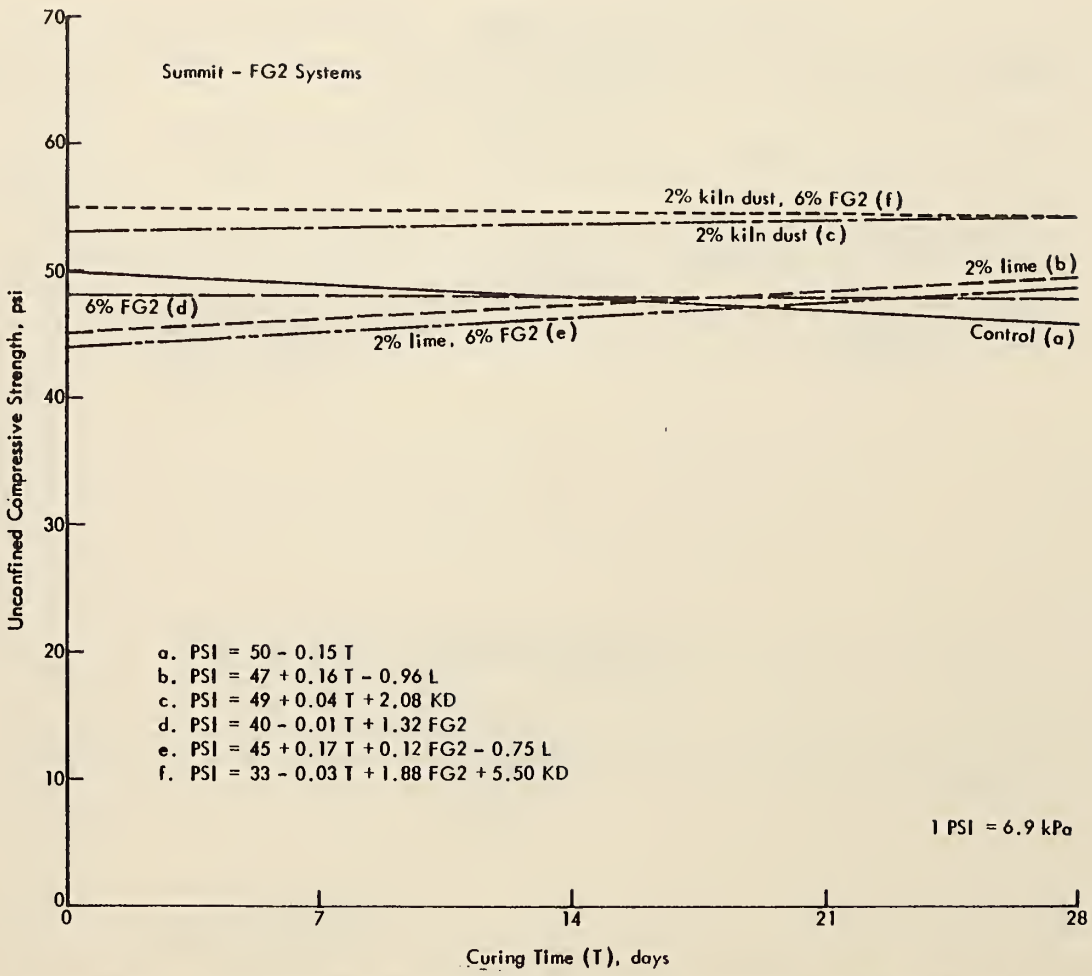
Summit - FG2 Systems
2% kiln dust, 6% FG2 (f)
2% kiln dust (c)
2% lime (b)
6% FG2 (d)
2% lime, 6% FG2 (e)
Control (a)
a. PSI = 50 - 0.15 T
b. PSI = 47 + 0.16 T - 0.96 L
c. PSI = 49 + 0.04 T + 2.08 KD
d. PSI = 40 - 0.01 T + 1.32 FG2
e. PSI = 45 + 0.17 T + 0.12 FG2 - 0.75 L
f. PSI = 33 - 0.03 T + 1.88 FG2 + 5.50 KD
1 PSI = 6.9 kPa
Unconfined Compressive Strength, psi
Curing Time (T), days
0
10
20
30
40
50
60
70
0
7
14
21
28

Figure 58. Linear regression plots of unconfined compressive strength versus curing time: Summit/FG2 systems.

TABLES

Table 1. Production rate of sulfate waste by source area.

Source Area	Location	Sulfate Waste Type	Sulfate Waste Annual Production Estimated tons/yr
*1	Tampa/Bartow, Florida	PG	24,000,000
2	New Orleans, Louisiana	PG	7,000,000
*3	Aurora, North Carolina	PG	3,500,000
*4	Joliet, Illinois	PG	2,000,000
		FG	100,000
5	Lake City, Florida	PG	2,000,000
*6	Houston, Texas	PG	1,500,000
7	Fort Madison, Iowa	PG	1,000,000
8	Pascagoula, Mississippi	PG	750,000
*9	Kansas City, Missouri	FG	1,000,000
10	Helena, Arkansas	PG	250,000
*11	Pittsburgh, Pennsylvania	FG	100,000
		AMD	100,000
12	Boston, Massachusetts	FG	50,000
13	Louisville, Kentucky	FG	50,000
14	Washington, D.C.	FG	30,000
15	Detroit, Michigan	FG	100,000
1-W	Pocatello/Conder, Idaho	PG	2,000,000
2-W	Central California	PG	900,000
		FG	20,000
3-W	Salt Lake City, Utah	PG	300,000
4-W	Kellogg, Idaho	PG	100,000
5-W	Four Corners Area, Arizona	FG	20,000

Key: * - Sulfate waste sample for experimental work obtained from this area.

PG - Phosphogypsum by-product of wet process phosphoric acid manufacture.

FG - Flue gas desulfurization solids from coal-fired electric power generating facilities with lime/limestone SO_x scrubbers.

AMD - Neutralized acid mine drainage solids.

Table 2. Soil family descriptions, representative soil series and associated sulfate waste sources.[a/]

Loamy, Siliceous, Hyperthermic:
Tampa/Bartow, Florida: Apopka, Kanapaha, Kendrick
Lake City, Florida: Blichton, Kendrick

Loamy, Siliceous, Thermic:
Aurora, North Carolina: Wagram

Loamy, Mixed, Noncalcareous, Hyperthermic:
Tampa/Bartow, Florida: Delray

Loamy, Mixed, Mesic:
Pittsburgh, Pennsylvania: Hazelton
Boston, Massachusetts: Hollis

Fine-Loamy, Siliceous, Thermic:
Tampa/Bartow, Florida: Rains, Vaucluse
Aurora, North Carolina: Norfolk, Pantego, Rains
Houston, Texas: Katy, Waller
Pascagoula, Mississippi: Goldsboro, Norfolk, Ruston, Saucier

Fine-Loamy, Siliceous, Mesic:
Washington, D.C.: Sassafras

Fine-Loamy, Mixed, Noncalcareous, Hyperthermic:
Tampa/Bartow, Florida: Chobee

Fine-Loamy, Mixed, Mesic:
Joliet, Illinois: Fox, Miami
Kansas City, Missouri: Gara, Shelby
Pittsburgh, Pennsylvania: Canfield, Clarksburg, Culleoka, Gilpin, Westmoreland
Washington, D.C.: Glenelg
Detroit, Michigan: Fox, Marlette

Fine-Loamy, Mixed, Acid, Mesic:
Pittsburgh, Pennsylvania: Atkins

Coarse-Loamy, Siliceous, Thermic:
Houston, Texas: Gessner
New Orleans, Louisiana: Prentiss
Pacagoula, Mississippi: Benndale, Escambia, McLaurin

Table 2. Soil family descriptions, representative soil series and associated sulfate waste sources[a/] (continued).

Coarse-Loamy, Mixed, Mesic:
Boston, Massachusetts: Charlton, Paxton, Woodbridge

Coarse-Loamy, Micaceous, Mesic:
Washington, D.C. Manor

Fine-Silty, Siliceous, Thermic:
Aurora, North Carolina: Exum

Fine-Silty, Mixed, Thermic:
Helena, Arkansas: Dundee, Memphis

Fine-Silty, Mixed, Nonacid, Thermic:
New Orleans, Louisiana: Commerce
Helena, Arkansas: Commerce

Fine-Silty, Mixed, Mesic:
Joliet, Illinois: Dodge, Muscatine, Sable, Tama
Kansas City, Missouri: Higginsville, Marshall
Fort Madison, Iowa: Tama
Louisville, Kentucky: Crider

Coarse-Silty, Mixed, Nonacid, Thermic:
New Orleans, Louisiana: Convent

Clayey, Mixed, Thermic:
Aurora, North Carolina: Bladen, Cape Fear, Craven, Lenoir
Washington, D.C.: Caroline

Clayey, Mixed, Mesic:
Pittsburgh, Pennsylvania: Wharton

Clayey, Kaolinitic, Thermic:
Aurora, North Carolina: Byars, Coxville
Pascagoula, Mississippi: Dunbar

Fine, Mixed, Thermic:
Kansas City, Missouri: Dennis, Hartwell

Fine, Mixed, Mesic:
Pittsburgh, Pennsylvania: Upshur
Louisville, Kentucky: Beasley, Eden, Lowell

Table 2. Soil family descriptions, representative soil series and associated sulfate waste sources[a/] (continued).

Fine, Montmorillonitic, Hyperthermic:
Tampa/Bartow, Florida: Fellowship, Martel
Lake City, Florida: Fellowship, Flemington

Fine, Montmorillonitic, Thermic:
Houston, Texas: Beaumont, Bernard, Edna, Harris, Lake Charles, Midland
Kansas City, Missouri: Summit

Fine, Montmorillonitic, Mesic:
Joliet, Illinois: Flanagan
Kansas City, Missouri: Adair, Grundy, Sharpsburg
Fort Madison, Iowa: Clinton, Keswick, Mahaska

Fine, Illitic, Mesic:
Joliet, Illinois: Elliott, Morley, Swygert
Pittsburgh, Pennsylvania: Mahoning
Detroit, Michigan: Hoytville, Nappanee

Very Fine, Montmorillonitic, Nonacid, Thermic:
New Orleans, Louisiana: Sharkey
Helena, Arkansas: Sharkey

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a/ Underscore indicates soil series chosen for experimental evaluation with sulfate waste.

Table 3. Type locations and sampling sites for soil series used for the experimental study.

Soil Series	Type Location County, State	Sampling Site County, State
Atkins	Raleigh, WV	Raleigh, WV
Charlton	New Haven, CN	New Haven, CN
Chobee	Okeechobee, FL	Okeechobee, FL
Commerce	Tensas, LA	Tensas, LA
Convent	St. John the Baptist, LA	St. James, LA
Coxville	Pitt, NC	Pitt, NC
Craven	Craven, NC	Craven, NC
Delray	Okeechobee, FL	Okeechobee, FL
Exum	Wayne, NC	Wayne, NC
Fellowship	Marion, FL	Marion, FL
Hartwell	Henry, MO	Henry, MO
Hazelton	Warren, PA	Warren, PA
Higginsville	Lafayette, MO	Lafayette, MO
Katy	Fort Bend, TX	Fort Bend, TX
Kendrick	Marion, FL	Marion, FL
Lake Charles	Fort Bend, TX	Fort Bend, TX
Mahoning	Lorain, OH	Lorain, OH
Manor	Prince Georges, MD	Prince Georges, MD
Memphis	Warren, MS	West Feliciana, LA
Miami	Rush, IN	Boone, IN
Norfolk	Robeson, NC	Robeson, NC
Prentiss	Lowndes, MS	St. Tammany, LA
Sassafras	New Castle, DE	Queen Annes, MD
Sharkey	West Feliciana, LA	St. John the Baptist, LA
Sharpsburg	Taylor, IA	Taylor, IA
Shelby	Adair, IA	Adair, IA
Summit	Rogers, OK	Woodson, KS
Tama	Tama, IA	Tama, IA
Upshur	Wood, WV	Wood, WV
Wagram	Scotland, NC	Scotland, NC
Wharton	Indiana, PA	Indiana, PA

Table 4. Chemical composition of sulfate wastes used in experimental study.

	PG1 (Florida)	PG2 (North Carolina)	PG3 (Texas)	FG1 (Illinois)	FG2 (Kansas)		AMD (Pennsylvania)
					As Collected	-40	
Calcium, % as CaO	23.6	25.4	26.0	30.3	13.9	41.2	22.8
Silica, % as SiO_2	18.0	11.8	13.5	24.4	43.1		12.1
Iron, % as Fe_2O_3	0.3	0.8	0.2	6.3	18.1	21.1	16.6
Aluminum, % as Al_2O_3	0.3	0.2	0.6	10.6	13.6		11.9
Sulfate, % as SO_3	32.7	38.5	42.2	12.6	0.7	2.7	1.7
Sulfite, % as SO_2	0.01	0.02	0.02	0.22	0.03	0.10	0.02
Phosphorus, % as P_2O_5	3.2	1.4	1.9	0.3	0.1	0.2	0.6
Loss on Ignition, %	16.6	17.9	19.7	13.6	5.8	32.2	27.5
Totals	94.71	95.32	104.12	98.32	95.33	97.50	93.22
Fluoride, ppm F	260	1,080	1,850	2	39	-	11
pH	4.3	2.8	4.0	8.6	7.8	7.8	7.2
Moisture, as received, %	23	17	60	50	28	-	70
Moisture, air dried, %	11	14	16	15	7	-	60

Table 5. Soil classification and physical property data for soils used in the experimental study.

Soil	Family[a]	AASHTO[c] Classification	% of Material Passing Sieve[a] No. 10 (2.0 mm)	No. 40 (0.425 mm)	No. 200 (0.075 mm)	Liquid Limit	Plastic Limit	Plasticity[b] Index	Maximum Dry[b] Density, pcf (AASHTO T 99)	Optimum Moisture[b] Content, %	pH[a]
Class I											
Atkins	Fine-loamy, mixed, acid, mesic	A-4	80-100	60-100	40-85	25	NP	NP	112	15	4.5-5.5
Charlton	Coarse-loamy, mixed mesic	A-4 (A-2-4)	60-90	50-70	20-60	31	NP	NP	106	16	4.5-6.0
Convent	Coarse-silty, mixed, nonacid, thermic	A-4	100	95-100	65-100	28	NP	NP	102	17	6.1-8.4
Coxville	Clayey, kaolinitic, thermic	A-4	100	91-98	53-81	23	14	9	116	13	4.5-5.5
Delray	Loamy, mixed, noncalcareous, hyperthermic	A-4	100	90-100	60-80	NP	NP	NP	102	12	4.5-5.5
Hazelton	Loamy-skeletal, mixed, mesic	A-4 (A-2-4)	55-80	50-70	20-55	20	NP	NP	112	15	3.6-5.5
Kendrick	Loamy, siliceous, hyperthermic	A-4 (A-2-4)	90-100	85-95	25-45	20	NP	NP	121	11	4.5-5.5
Manor	Coarse-loamy, micaceous, mesic	A-4 (A-2-4)	N.A.[b]			35	NP	NP	113	16	N.A.
Norfolk	Fine-loamy, siliceous, thermic	A-4	91-100	70-96	30-48	16	11	5	126	10	4.5-5.5
Prentiss	Coarse-loamy, siliceous, thermic	A-4	100	70-100	40-75	20	NP	2	115	12	4.5-5.5
Wagram	Loamy, siliceous, thermic	A-4 (A-2-4)	90-100	66-90	31-50	NP	NP	NP	124	8	4.5-5.5
Class II											
Commerce	Fine-silty, mixed, nonacid, thermic	A-6	100	100	85-100	36	22	14	105	18	6.1-8.4
Exum	Fine-silty, siliceous, thermic	A-6	N.A.			34	17	17	109	17	N.A.
Mahoning	Fine, illitic, mesic	A-7-6	90-100	85-100	80-95	42	22	20	104	20	4.5-6.5
Memphis	Fine-silty, mixed, thermic	A-7-6	100	100	90-100	44	22	22	100	20	4.5-6.0
Miami	Fine-loamy, mixed, mesic	A-6	89-97	78-95	64-95	34	18	16	108	17	5.6-6.0
Sassafras	Fine-loamy, siliceous, mesic	A-6	N.A.			28	14	14	117	13	N.A.
Shelby	Fine-loamy, mixed, mesic	A-7-6	85-98	75-90	55-70	47	23	24	102	20	5.6-6.0
Tama	Fine-silty, mixed, mesic	A-7-6	100	100	95-100	50	28	22	98	23	5.1-5.5
Wharton	Clayey, mixed, mesic	A-7-6	70-100	65-95	60-90	47	24	23	99	24	4.5-5.5
Class III											
Chobee	Fine loamy, mixed, noncalcareous hyperthermic	A-7-6 (A-2-7)	100	85-99	25-45	49	18	31	105	20	7.4-8.4
Craven	Clayey, mixed, thermic	A-7-6	100	90-100	70-95	62	25	37	94	26	4.5-5.5
Hartwell	Fine, mixed, thermic	A-7-6	100	95-100	90-100	53	24	29	100	21	5.1-6.5
Higginsville	Fine-silty, mixed, mesic	A-7-6	100	95-100	90-100	65	28	37	94	25	5.1-6.5
Katy	Fine-loamy, siliceous, thermic	A-7-6	98-100	98-100	55-75	63	18	45	100	21	5.1-7.3
Upshur	Fine, mixed, mesic	A-7-6	70-100	55-100	55-100	54	28	26	98	24	4.5-7.3

Table 5. Soil classification and physical property data for soils used in the experimental study (continued).

Soil	Family[a]	AASHTO[c] Classification	% of Material Passing Sieve[a] No. 10 (2.0 mm)	No. 40 (0.425 mm)	No. 200 (0.075 mm)	Liquid Limit	Plastic Limit	Plasticity[b] Index	Maximum Dry[b] Density, pcf (AASHTO T 99)	Optimum Moisture[b] Content, %	pH[a]
Class IV											
Fellowship	Fine, montmorillonitic, hyperthermic	A-7-6	N.A.			51	28	23	87	30	N.A.
Lake Charles	Fine, montmorillonitic, thermic	A-7-6	98-100	80-100	75-100	60	27	33	97	25	6.6-8.4
Sharkey	Very fine, montmorillonitic, nonacid, thermic	A-7-5	100	100	95-100	91	30	61	87	26	5.1-8.4
Sharpsburg	Fine, montmorillonitic, mesic	A-7-6	100	100	95-100	60	27	33	95	23	5.6-6.5
Summit	Fine, montmorillonitic, thermic	A-7-5	100	96-100	80-99	69	30	39	96	26	N.A.

a/ Obtained from SCS soil survey interpretations for individual soil series.
b/ Determined from laboratory characterization.
c/ Two classes are shown for soils with a range of particle size distribution greater than and less than 35% passing a No. 200 sieve. The value in parenthesis is for soil with less than 35% passing.
d/ Not available.

Table 6. Linear regression analysis of liquid limit (LL) data for soil/sulfate waste systems. LL as percent moisture.

Soils Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class I Soils: Plasticity Index NP-10					
Convent	PG1	LL = 28 + 0.00 SW	-	-	-
Delray	PG1	Nonplastic	-	-	-
Kendrick	PG1	LL = 20 - 0.02 SW	0.029	0.08	NS
Norfolk	PG1	LL = 16 + 0.10 SW	0.314	0.11	NS
Coxville	PG2	LL = 23 + 0.16 SW	0.751	0.07	0
Norfolk	PG2	LL = 16 + 0.07 SW	0.467	0.05	NS
Prentiss	PG2	LL = 20 + 0.10 SW	0.714	0.04	0
Wagram	PG2	Nonplastic	-	-	-
Convent	PG3	LL = 28 + 0.13 SW	0.467	0.10	NS
Prentiss	PG3	LL = 20 + 0.13 SW	0.467	0.10	NS
Atkins	FG1	LL = 25 + 0.25 SW	0.966	0.03	*
Charlton	FG1	LL = 31 + 0.40 SW	0.969	0.05	*
Hazelton	FG1	LL = 20 + 0.43 SW	0.981	0.04	**
Manor	FG1	LL = 35 + 0.31 SW	0.889	0.08	+
Atkins	AMD	LL = 25 + 0.42 SW	0.988	0.03	**
Charlton	AMD	LL = 31 + 0.52 SW	0.950	0.09	*
Hazelton	AMD	LL = 20 + 0.74 SW	0.669	0.37	0
Manor	AMD	LL = 35 + 0.58 SW	0.994	0.03	**
Class II Soils: Plasticity Index 10-25					
Commerce	PG1	LL = 36 + 0.00 SW	-	-	-
Memphis	PG1	LL = 44 - 0.33 SW	1.000	0.00	***
Exum	PG2	LL = 33 - 0.31 SW	0.724	0.14	0
Miami	PG2	LL = 34 + 0.17 SW	0.771	0.07	0

Table 6. Linear regression analysis of liquid limit (LL) data for soil/sulfate waste systems. LL as percent moisture (continued).

Soils Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Commerce	PG3	LL = 36 - 0.10 SW	0.714	0.04	0
Mahoning	PG3	LL = 41 - 0.27 SW	0.400	0.23	NS
Memphis	PG3	LL = 43 + 0.00 SW	0.000	0.00	NS
Tama	PG3	LL = 50 - 0.17 SW	0.771	0.07	0
Mahoning	FG1	LL = 42 + 0.22 SW	0.795	0.08	0
Miami	FG1	LL = 35 + 0.24 SW	0.350	0.23	NS
Sassafras	FG1	LL = 28 + 0.31 SW	0.889	0.08	+
Tama	FG1	LL = 51 + 0.30 SW	0.281	0.34	NS
Wharton	FG1	LL = 47 + 0.40 SW	0.969	0.05	*
Shelby	FG2	LL = 47 - 0.57 SW	0.989	0.04	**
Mahoning	AMD	LL = 42 + 0.42 SW	0.989	0.03	**
Miami	AMD	LL = 34 + 0.33 SW	1.000	0.00	***
Sassafras	AMD	LL = 28 + 0.32 SW	0.917	0.07	*
Shelby	AMD	LL = 47 + 0.14 SW	0.584	0.09	NS
Tama	AMD	LL = 50 + 0.28 SW	0.687	0.13	0
Wharton	AMD	LL = 48 + 0.40 SW	0.741	0.17	0
Class III Soils: Plasticity Index > 25, monmontmorillonitic					
Chobee	PG1	LL = 49 - 0.20 SW	0.663	0.10	0
Craven	PG2	LL = 61 - 0.88 SW	0.889	0.22	+
Katy	PG3	LL = 61 - 1.04 SW	0.826	0.34	+
Higginsville	FG1	LL = 65 + 0.09 SW	0.771	0.03	+
Upshur	FG1	LL = 54 + 0.35 SW	0.910	0.08	*
Hartwell	FG2	LL = 53 - 0.71 SW	0.940	0.13	*
Higginsville	FG2	LL = 66 - 0.71 SW	0.940	0.13	*
Upshur	AMD	LL = 54 + 0.50 SW	0.967	0.07	*

Table 6. Linear regression analysis of liquid limit (LL) data for soil/sulfate waste systems. LL as percent moisture (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class IV Soils: Plasticity Index > 20, montmorillonitic					
Fellowship	PG1	LL = 51 - 0.29 SW	0.714	0.13	0
Sharkey	PG1	LL = 91 - 0.68 SW	0.805	0.24	0
Sharpsburg	PG2	LL = 60 - 0.66 SW	0.978	0.07	*
Lake Charles	PG3	LL = 61 - 0.45 SW	0.760	0.18	0
Sharkey	PG3	LL = 89 - 0.90 SW	0.625	0.49	NS
Sharpsburg	PG3	LL = 60 - 0.71 SW	0.940	0.13	*
Sharpsburg	FG1	LL = 61 - 0.06 SW	0.051	0.17	NS
Sharpsburg	FG2	LL = 59 - 0.70 SW	0.910	0.16	*
Summit	FG2	LL = 68 - 1.12 SW	0.947	0.19	*
Sharpsburg	AMD	LL = 60 - 0.21 SW	0.314	0.22	NS

Key:
Sulfate Wastes (SW):
PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG1 - Flue Gas Desulfurization Solids (Illinois)
FG2 - Flue Gas Desulfurization Solids (Kansas)
AMD - Acid Mine Drainage Neutrilization Solids (Pennsylvania)

*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
0 = Significant at 80% level
NS = Significance level below 80%

Table 7. Linear regression analysis of plasticity index (PI) data for soil/sulfate waste systems. PI as percent moisture difference.

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class I Soils: Plasticity Index NP-10					
Convent	PG1	Nonplastic	-	-	-
Delray	PG1	Nonplastic	-	-	-
Kendrick	PG1	Nonplastic	-	-	-
Norfolk	PG1	Nonplastic	-	-	-
Coxville	PG2	PI = 9 + 0.01 SW	0.010	0.07	NS
Norfolk	PG2	PI = 5 - 0.19 SW	0.714	0.09	0
Prentiss	PG2	Nonplastic	-	-	-
Wagram	PG2	Nonplastic	-	-	-
Convent	PG3	Nonplastic	-	-	-
Prentiss	PG3	Nonplastic	-	-	-
Atkins	FG1	Nonplastic	-	-	-
Charlton	FG1	Nonplastic	-	-	-
Hazelton	FG	Nonplastic	-	-	-
Manor	FG1	Nonplastic	-	-	-
Atkins	AMD	Nonplastic	-	-	-
Charlton	AMD	Nonplastic	-	-	-
Hazelton	AMD	Nonplastic	-	-	-
Manor	AMD	Nonplastic	-	-	-
Class II Soils: Plasticity Index 10-25					
Commerce	PG1	PI = 15 - 0.08 SW	0.229	0.10	NS
Memphis	PG1	PI = 22 - 0.33 SW	1.000	0.00	***
Exum	PG2	PI = 17 - 0.24 SW	0.940	0.04	*
Miami	PG2	PI = 17 + 0.16 SW	0.435	0.13	NS

Table 7. Linear regression analysis of plasticity index (PI) data for soil/sulfate waste systems. PI as percent moisture difference (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Commerce	PG3	PI = 14 - 0.28 SW	0.890	0.07	+
Mahoning	PG3	PI = 20 - 0.35 SW	0.910	0.11	+
Memphis	PG3	PI = 21 + 0.01 SW	0.001	0.26	NS
Tama	PG3	PI = 22 - 0.01 SW	0.010	0.07	NS
Mahoning	FG1	PI = 20 + 0.06 SW	0.257	0.10	NS
Miami	FG1	PI = 18 + 0.01 SW	0.000	0.33	NS
Sassafras	FG1	PI = 14 - 0.11 SW	0.514	0.08	NS
Tama	FG1	PI = 24 + 0.42 SW	0.238	0.53	NS
Wharton	FG1	PI = 23 - 0.05 SW	0.065	0.13	NS
Shelby	FG2	PI = 24 - 0.31 SW	0.889	0.08	+
Mahoning	AMD	PI = 20 - 0.20 SW	0.662	0.14	NS
Miami	AMID	PI = 16 - 0.08 SW	0.229	0.10	NS
Sassafras	AMD	PI - 15 - 0.17 SW	0.462	0.13	NS
Shelby	AMD	PI - 24 - 0.36 SW	0.938	0.968	*
Tama	AMD	PI = 22 - 0.07 SW	0.074	0.17	NS
Wharton	AMD	PI = 24 - 0.18 SW	0.295	0.20	NS
Class III Soils: Plasticity Index > 25, monmontmorillonitic					
Chobee	PG1	PI = 31 - 0.35 SW	0.909	0.08	*
Craven	PG2	PI = 36 - 0.50 SW	0.577	0.31	NS
Katy	PG3	PI = 44 - 1.05 SW	0.873	0.28	+
Higginsville	FG1	PI = 38 - 0.04 SW	0.011	0.25	NS
Upshur	FG1	PI = 27 + 0.13 SW	0.280	0.15	NS
Hartwell	FG2	PI = 29 - 0.43 SW	0.981	0.990	**
Higginsville	FG2	PI = 38 - 0.30 SW	0.522	0.21	NS
Upshur	AMD	PI = 26 + 0.09 SW	0.771	0.03	+

Table 7. Linear regression analysis of plasticity index (PI) data for soil/sulfate waste systems. PI as percent moisture difference (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class IV Soils: Plasticity Index > 20, montmorillonitic					
Fellowship	PG1	PI = 23 - 0.10 SW	0.143	0.16	NS
Sharkey	PG1	PI = 61 - 0.72 SW	0.937	0.13	*
Sharpsburg	PG2	PI = 33 - 0.66 SW	0.978	0.07	*
Lake Charles	PG3	PI = 34 - 0.11 SW	0.171	0.18	NS
Sharkey	PG3	PI = 58 - 1.19 SW	0.721	0.52	0
Sharpsburg	PG3	PI = 33 - 0.74 SW	0.966	0.10	*
Sharpsburg	FG1	PI = 34 + 0.00 SW	0.000	0.20	NS
Sharpsburg	FG2	PI = 32 - 0.52 SW	0.752	0.21	0
Summit	FG2	PI = 38 - 0.62 SW	0.921	0.13	*
Sharpsburg	AMD	PI = 32 - 0.30 SW	0.522	0.21	NS

Key:
Sulfate Wastes (SW):
PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG1 - Flue Gas Desulfurization Solids (Illinois)
FG2 - Flue Gas Desulfurization Solids (Kansas)
AMD - Acid Mine Drainage Neutrilization Solids (Pennsylvania)

*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
0 = Significant at 80% level
NS = Significance level below 80%

Table 8. Linear regression analysis of optimum moisture (OM) data for soil/sulfate waste systems. OM as percent moisture at maximum density.

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class I Soils: Plasticity Index NP-10					
Convent	PG1	OM = 17 + 0.35 SW	0.909	0.08	*
Delray	PG1	OM = 12 + 0.03 SW	0.023	0.13	NS
Kendrick	PG1	OM = 12 + 0.21 SW	0.265	0.25	NS
Norfolk	PG1	OM = 10 + 0.12 SW	0.439	0.10	NS
Coxville	PG2	OM = 13 + 0.06 SW	0.257	0.07	NS
Norfolk	PG2	OM = 10 + 0.02 SW	0.028	0.08	NS
Prentiss	PG2	OM = 12 + 0.26 SW	0.771	0.10	0
Wagram	PG2	OM = 8 + 0.25 SW	0.965	0.03	*
Convent	PG3	OM = 17 + 0.21 SW	0.691	0.10	0
Prentiss	PG3	OM = 12 + 0.15 SW	0.914	0.03	*
Atkins	FG1	OM = 15 + 0.24 SW	0.940	0.04	*
Charlton	FG1	OM = 17 + 0.44 SW	8.889	0.11	+
Hazelton	FG1	OM = 15 + 0.28 SW	0.687	0.13	0
Manor	FG1	OM = 16 + 0.49 SW	0.991	0.03	**
Atkins	AMD	OM = 15 + 0.46 SW	0.941	0.05	*
Charlton	AMD	OM = 16 + 0.60 SW	0.986	0.05	**
Hazelton	AMD	OM = 15 + 0.47 SW	0.827	0.15	+
Manor	AMD	OM = 17 + 0.16 SW	0.435	0.13	NS
Class II Soils: Plasticity Index 10-25					
Commerce	PG1	OM = 18 + 0.36 SW	0.957	0.07	*
Memphis	PG1	OM = 20 + 0.35 SW	0.910	0.08	*
Exum	PG2	OM = 17 + 0.09 SW	0.771	0.03	+
Miami	PG2	OM = 17 + 0.21 SW	0.691	0.10	0

Table 8. Linear regression analysis of optimum moisture (OM) data for soil/sulfate waste systems. OM as percent moisture at maximum density (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Commerce	PG3	OM = 18 + 0.17 SW	0.771	0.07	0
Mahoning	PG3	OM = 21 + 0.12 SW	0.138	0.22	NS
Memphis	PG3	OM = 19 + 0.24 SW	0.510	0.16	NS
Tama	PG3	OM = 23 - 0.04 SW	0.057	0.11	NS
Mahoning	FG1	OM = 20 + 0.32 SW	0.917	0.07	*
Miami	FG1	OM = 18 + 0.26 SW	0.771	0.10	0
Sassafras	FG1	OM = 13 + 0.15 SW	0.914	0.03	*
Tama	FG1	OM = 23 + 0.20 SW	0.663	0.10	0
Wharton	FG1	OM = 24 + 0.26 SW	0.771	0.10	0
Shelby	FG2	OM = 20 - 0.15 SW	0.914	0.03	*
Mahoning	AMD	OM = 20 + 0.46 SW	0.914	0.10	*
Miami	AMD	OM = 18 + 0.47 SW	0.826	0.15	+
Sassafras	AMD	OM = 13 + 0.39 SW	0.941	0.07	*
Shelby	AMD	OM = 20 + 0.06 SW	0.257	0.07	NS
Tama	AMD	OM = 23 + 0.42 SW	0.988	0.03	**
Wharton	AMD	OM = 25 + 0.29 SW	0.714	0.13	0
Class III Soils: Plasticity Index > 25, montmorillonitic					
Chobee	PG1	OM = 20 + 0.07 SW	0.467	0.05	NS
Craven	PG2	OM = 27 - 0.11 SW	0.171	0.18	NS
Katy	PG3	OM = 21 - 0.13 SW	0.280	0.21	NS
Higginsville	FG1	OM = 25 + 0.30 SW	0.784	0.11	0
Upshur	FG1	OM = 24 - 0.11 SW	0.257	0.14	NS
Hartwell	FG2	OM = 22 - 0.59 SW	0.538	0.39	NS
Higginsville	FG2	OM = 25 - 0.14 SW	0.584	0.09	NS
Upshur	AMD	OM = 24 - 0.10 SW	0.714	0.04	0

Table 8. Linear regression analysis of optimum moisture (OM) data for soil/sulfate waste systems. OM as percent moisture at maximum density (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index of Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class IV Soils: Plasticity Index > 20, montmorillonitic					
Fellowship	PG1	OM = 30 - 0.01 SW	0.010	0.07	NS
Sharkey	PG1	OM = 27 + 0.37 SW	0.737	0.16	0
Sharpsburg	PG2	OM = 23 + 0.32 SW	0.917	0.07	*
Lake Charles	PG3	OM = 24 - 0.29 SW	0.584	0.17	NS
Sharkey	PG3	OM = 25 + 0.66 SW	0.925	0.13	*
Sharpsburg	PG3	OM = 24 + 0.13 SW	0.280	0.15	NS
Sharpsburg	FG1	OM = 24 + 0.44 SW	0.889	0.11	+
Sharpsburg	FG2	OM = 24 - 0.23 SW	0.411	0.19	NS
Summit	FG2	OM = 26 - 0.47 SW	0.915	0.10	*
Sharpsburg	AMD	OM = 23 + 0.57 SW	0.989	0.04	**

Key:
Sulfate Wastes (SW):
PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG1 - Flue Gas Desulfurization Solids (Illinois)
FG2 - Flue Gas Desulfurization Solids (Kansas)
AMD - Acid Mine Drainage Neutrilization Solids (Pennsylvania)

*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
0 = Significant at 80% level
NS = Significance level below 80%

Table 9. Linear regression analysis of maximum density (MD) data for soil/sulfate waste systems. MD as lb/cu ft (1 lb/cu ft = 16.0 kg/cu m).

Soil Series	Sulfate Waste	Linear Regression Equation	Index Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class I Soils: Plasticity Index NP-10					
Convent	PG1	MD = 102 - 0.35 SW	0.909	0.08	*
Delray	PG1	MD = 102 - 0.26 SW	0.771	0.10	0
Kendrick	PG1	MD = 121 - 0.19 SW	0.714	0.09	0
Norfolk	PG1	MD = 126 - 0.31 SW	0.889	0.08	+
Coxville	PG2	MD = 116 - 0.04 SW	0.057	0.11	NS
Norfolk	PG2	MD = 125 - 0.01 SW	0.003	0.13	NS
Prentiss	PG2	MD = 115 - 0.25 SW	0.714	0.04	0
Wagram	PG2	MD = 124 - 0.51 SW	0.992	0.03	**
Convent	PG3	MD = 102 - 0.35 SW	0.909	0.08	*
Prentiss	PG3	MD = 114 - 1.18 SW	0.947	0.20	*
Atkins	FG1	MD = 112 - 0.40 SW	0.967	0.07	*
Charlton	FG1	MD = 105 - 0.52 SW	0.873	0.14	+
Hazelton	FG1	MD = 112 - 0.72 SW	0.982	0.07	**
Manor	FG1	MD = 113 - 1.02 SW	0.943	0.18	*
Atkins	AMD	MD = 112 - 0.985SW	0.987	0.08	**
Charlton	AMD	MD = 105 - 0.59 SW	0.907	0.10	*
Hazelton	AMD	MD = 112 - 0.92 SW	0.978	0.10	*
Manor	AMD	MD = 112 - 0.58 SW	0.686	0.28	0
Class II Soils: Plasticity Index 10-25					
Commerce	PG1	MD = 105 - 0.41 SW	0.895	0.10	+
Memphis	PG1	MD = 100 - 0.10 SW	0.714	0.04	0
Exum	PG2	MD = 109 + 0.00 SW	-	-	-
Miami	PG2	MD = 108 - 0.25 SW	0.965	0.03	*

Table 9. Linear regression analysis of maximum density (MD) data for soil/sulfate waste systems. MD as lb/cu ft (1 lb/cu ft = 16.0 kg/cu m) (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Commerce	PG3	MD = 105 - 0.39 SW	0.814	0.13	+
Mahoning	PG3	MD = 103 - 0.16 SW	0.435	0.13	NS
Memphis	PG3	MD = 100 + 0.29 SW	0.714	0.13	0
Tama	PG3	MD = 98 - 0.07 SW	0.467	0.05	NS
Mahoning	FG1	MD = 103 - 0.43 SW	0.771	0.16	0
Miami	FG1	MD = 108 - 0.63 SW	0.943	0.11	*
Sassafras	FG1	MD = 117 - 0.43 SW	0.981	0.04	**
Tama	FG1	MD = 97 - 0.52 SW	0.873	0.14	+
Wharton	FG1	MD = 98 - 0.41 SW	0.494	0.29	NS
Shelby	FG2	MD = 102 + 0.33 SW	1.000	0.00	***
Mahoning	AMD	MD = 104 - 0.70 SW	0.954	0.11	*
Miami	AMD	MD = 108 - 0.69 SW	0.974	0.08	*
Sassafras	AMD	MD = 117 - 0.97 SW	0.965	0.13	*
Shelby	AMD	MD = 102 - 0.18 SW	0.382	0.16	NS
Tama	AMD	MD = 98 - 0.69 SW	0.974	0.08	*
Wharton	AMD	MD = 99 - 0.73 SW	0.991	0.05	**
Class III Soils: Plasticity Index > 25, montmorillonitic					
Chobee	PG1	MD = 105 - 0.16 SW	0.751	0.07	0
Craven	PG2	MD = 95 - 0.13 SW	0.082	0.31	NS
Katy	PG3	MD = 100 + 0.08 SW	0.076	0.19	NS
Higginsville	FG1	MD = 93 - 0.43 SW	0.771	0.16	0
Upshur	FG1	MD = 99 + 0.10 SW	0.143	0.16	NS
Hartwell	FG2	MD = 99 + 0.67 SW	0.714	0.30	0
Higginsville	FG2	MD = 94 + 0.06 SW	0.085	0.13	NS
Upshur	AMD	MD = 99 - 0.05 SW	0.065	0.13	NS

Table 9. Linear regression analysis of maximum density (MD) data for soil/sulfate waste systems. MD as lb/cu ft (1 lb/cu ft = 16.0 kg/cu m) (continued).

Soil Series	Sulfate Waste	Linear Regression Equation	Index Determination r^2	Standard Deviation Sulfate Waste Coefficient	Statistical Significance
Class IV Soils: Plasticity Index > 20, montmorillonitic					
Fellowship	PG1	MD = 87 + 0.13 SW	0.467	0.10	NS
Sharkey	PG1	MD = 87 + 0.15 SW	0.914	0.03	*
Sharpsburg	PG2	MD = 95 - 0.24 SW	0.940	0.04	*
Lake Charles	PG3	MD = 97 - 0.21 SW	0.691	0.10	0
Sharkey	PG3	MD = 87 - 0.09 SW	0.771	0.03	+
Sharpsburg	PG3	MD = 95 - 0.07 SW	0.467	0.05	NS
Sharpsburg	FG1	MD = 95 - 0.50 SW	0.967	0.07	*
Sharpsburg	FG2	MD = 95 + 0.41 SW	0.704	0.19	0
Summit	FG2	MD = 96 - 0.02 SW	0.029	0.08	NS
Sharpsburg	AMD	MD = 95 - 0.67 SW	1.000	0.00	***

Key:
Sulfate Wastes (SW):
PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG1 - Flue Gas Desulfurization Solids (Illinois)
FG2 - Flue Gas Desulfurization Solids (Kansas)
AMD - Acid Mine Drainage Neutrilization Solids (Pennsylvania)

*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
0 = Significant at 80% level
NS = Significance level below 80%

Table 10. Linear regression analysis of unconfined compressive strengths of untreated soils (as a function of moisture content and curing time). Linear regression coefficients standard deviations, and statistical significances.

Control Systems	Moisture, PSI/% H_2O			Time, PSI/Day		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class I Soils: Plasticity Index NP-10						
Atkins DF = 7, r^2 = 0.424	-12.76	5.85	ns	0.04	0.16	ns
Charlton DF = 2, r^2 = 0.898	-7.27	2.09	+	0.00	0.08	ns
Convent DF = 2, r^2 = 0.213	0.00	--	ns	0.11	0.15	ns
Coxville DF = 1, r^2 = 0.439	4.87	6.52	ns	0.22	0.25	ns
Delray DF = 3, r^2 = 0.200	0.00	--	ns	0.02	0.03	ns
Hazelton DF = 7, r^2 = 0.254	-3.02	2.19	ns	0.06	0.10	ns
Kendrick DF = 2, r^2 = 0.762	0.00	--	ns	0.13	0.07	ns
Manor DF = 1, r^2 = 0.183	0.46	2.95	ns	-0.05	0.14	ns
Norfolk DF = 2, r^2 = 0.987	3.08	0.61	*	0.27	0.03	*
Prentiss DF = 13, r^2 = 0.090	-2.45	2.94	ns	-0.01	0.11	ns
Wagram DF = 1, r^2 = 0.999	-2.71	6.00	ns	0.29	0.60	ns
Class II Soils: Plasticity Index 10-25						
Commerce DF = 7, r^2 = 0.100	0.00	--	ns	0.08	0.09	ns
Exum DF = 2, r^2 = 0.863	-3.07	0.89	+	-0.04	0.03	ns
Mahoning DF = 13, r^2 = 0.288	-0.87	1.07	ns	-0.28	0.12	*
Memphis DF = 2, r^2 = 0.791	-8.18	3.00	+	0.00	0.13	ns
Miami DF = 6, r^2 = 0.047	1.16	2.13	ns	-0.05	0.18	ns
Sassafras DF = 6, r^2 = 0.812	-6.04	1.60	**	-0.21	0.13	ns
Shelby DF = 10, r^2 = 0.510	-4.92	1.55	**	-0.02	0.16	ns
Tama DF = 14, r^2 = 0.012	-0.54	1.52	ns	-0.03	0.13	ns
Wharton DF = 1, r^2 = 0.155	-4.73	12.09	ns	0.23	0.54	ns

Table 10. Linear regression analysis of unconfined compressive strengths of untreated soils (as a function of moisture content and curing time). Linear regression coefficients, standard deviations, and statistical significances (continued).

Control Systems	Moisture, PSI/% H_2O			Time, PSI/Day		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic						
Chobee DF = 3, r^2 = 0.895	2.00	1.15	ns	0.30	0.08	*
Craven DF = 2, r^2 = 0.170	-2.89	5.27	ns	0.06	0.19	ns
Hartwell DF = 9, r^2 = 0.377	-5.06	2.21	*	0.22	0.20	ns
Higginsville DF = 5, r^2 = 0.107	2.39	5.88	ns	-0.22	0.30	ns
Katy DF = 9, r^2 = 0.260	-0.91	2.82	ns	-0.21	0.15	ns
Upshur DF = 2, r^2 = 0.897	0.16	1.54	ns	-0.34	0.11	+
Class IV Soils: Plasticity Index > 20, Montmurillonitic						
Fellowship DF = 3, r^2 = 0.200	5.50	2.69	ns	0.24	0.12	ns
Lake Charles DF = 9, r^2 = 0.097	-1.20	2.66	ns	-0.11	0.11	ns
Sharkey DF = 2, r^2 = 0.872	3.56	0.97	+	0.00	0.01	ns
Sharpsburg DF = 22, r^2 = 0.077	0.85	0.70	ns	-0.05	0.08	ns
Summit DF = 7, r^2 = 0.127	1.24	1.94	ns	-0.15	0.15	ns

Key:
DF = Degrees of Freedom (number of specimens - 3)
r^2 = Index of determination (square of correlation coefficient)
*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
ns = Significance below 90% level

1 psi = 6.9 kPa

Table 11. Linear regression analysis of unconfined compressive strengths of soils treated with sulfate waste (aa s function of moisture content, curing time, and sulfate wsste content). Linear regression coefficients, standsrd deviations, and statisticsl signific snces.

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance
			Class I Soils: Plasticity Index WP-10						
Delray PG1 DF = 11, r^2 = 0.254	0.14	0.26	NS	0.00	0.03	NS	-0.01	0.06	NS
Kendrick PG1 DF = 11, r^2 = 0.845	-12.24	1.65	***	0.10	0.04	*	2.86	0.42	***
Coxville PG2 DF = 15, r^2 = 0.640	-2.57	1.49	NS	-0.04	0.07	NS	-0.50	0.27	+
Norfolk PG2 DF = 16, r^2 = 0.642	-3.66	0.70	***	0.03	0.12	NS	0.33	0.13	NS
Prentiss PG2 DF = 25, r^2 = 0.248	-3.83	1.63	*	0.07	0.06	NS	0.65	0.37	+
Wagram PG2 DF = 14, r^2 = 0.828	-1.08	0.69	NS	-0.03	0.02	NS	0.74	0.22	**
Convent PG3 DF = 16, r^2 = 0.169	-0.29	0.56	NS	-0.03	0.04	NS	-0.08	0.13	NS
Prentiss PG3 DF = 45, r^2 = 0.116	-0.04	0.50	NS	-0.06	0.04	NS	0.11	0.15	NS
Atkins FG1 DF = 20, r^2 = 0.384	-4.19	1.82	*	-0.16	0.09	+	0.82	0.51	NS
Hazelton FG1 DF = 20, r^2 = 0.535	-2.23	0.47	***	0.07	0.06	NS	0.65	0.17	**
Atkins AMD DF = 21, r^2 = 0.101	-2.64	1.75	NS	0.06	0.11	NS	1.14	0.83	NS
Charlton AMD DF = 16, r^2 = 0.244	-1.03	0.62	NS	-0.08	0.07	NS	0.59	0.37	NS
Hazelton AMD DF - 20, r^2 = 0.081	0.26	0.38	NS	-0.09	0.09	NS	-0.15	0.28	NS
Msnor AMD DF = 13, r^2 = 0.176	-1.19	0.62	+	0.12	0.07	NS	0.98	0.18	***

Table 11. Linear regression analysis of unconfined compressive strengths of soils treated with sulfate waste (as a function of moisture content, curing time, and sulfate waste content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class II Soils: Plasticity Index 10-25									
Exum PG2 DF = 16, r^2 = 0.598	-2.15	1.10	+	-0.05	0.05	NS	-0.20	0.22	NS
Miami PG2 DF = 20, r^2 = 0.513	-0.60	0.77	NS	-0.02	0.08	NS	-0.64	0.34	+
Commerce PG3 DF = 44, r^2 = 0.130	-1.33	1.60	NS	0.02	0.06	NS	0.54	0.30	+
Mahoning PG3 DF = 45, r^2 = 0.065	-0.78	0.48	NS	0.07	0.10	NS	-0.11	0.22	NS
Memphis PG3 DF = 16, r^2 = 0.699	-0.44	0.82	NS	-0.04	0.07	NS	-0.99	0.23	***
Tama PG3 DF = 47, r^2 = 0.238	-0.70	0.84	NS	-0.16	0.08	+	-0.45	0.23	+
Mahoning FG1 DF = 16, r^2 = 0.453	-0.98	0.93	NS	-0.26	0.10	*	-1.04	0.46	*
Sassafras FG1 DF = 17, r^2 = 0.453	-2.35	1.35	+	-0.37	0.11	**	0.76	0.32	*
Shelby FG2 DF = 37, r^2 = 0.693	-7.32	0.82	***	-0.02	0.07	NS	-2.11	0.29	***
Mshoning AMD DF = 27, r^2 = 0.503	-1.75	0.71	*	-0.25	0.07	**	0.11	0.27	NS
Miami AMD DF = 17, r^2 = 0.299	-0.88	0.69	NS	0.14	0.10	NS	-0.03	0.39	NS
Sassafras AMD DF = 19, r^2 = 0.605	-7.12	1.42	***	-0.04	0.12	NS	3.25	0.61	***
Shelby AMD DF - 24, r^2 = 0.169	-4.78	1.77	*	0.05	0.10	NS	0.69	0.23	**
Tama AMD DF = 28, r^2 = 0.123	-0.95	0.30	**	-0.06	0.09	NS	-0.18	0.20	NS
Wharton AMD DF = 13, r^2 = 0.615	0.24	0.79	NS	0.14	0.07	+	0.79	0.21	**

Table 11. Linear regreasion analysis of unconfined compressive strengths of soils treated with sulfate waste (as a function of moisture content, curing time, and sulfate waste content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regreasion Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regreasion Coefficient	Standard Deviation	Signifi-cance
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic									
Chobee PG1 DF = 14, r^2 = 0.821	-4.02	1.05	**	-0.11	0.09	NS	-0.37	0.20	+
Craven PG2 DF = 16, r^2 = 0.709	-3.98	0.77	***	-0.05	0.08	NS	-1.23	0.22	***
Katy PG3 DF = 42, r^2 = 0.587	0.46	0.49	NS	-0.22	0.06	***	-0.75	0.16	***
Hartwell FG2 DF = 42, r^2 = 0.656	-2.64	0.50	***	0.37	0.01	***	-0.62	0.17	***
Higginsville FG2 DF = 26, r^2 = 0.283	-1.59	1.15	NS	-0.11	0.13	NS	0.15	0.50	NS
Upshur AMD DF = 15, r^2 = 0.519	-2.70	1.15	*	0.01	0.14	NS	-0.28	0.93	NS
Class IV Soils: Plasticity Index > 20, Montmorillonitic									
Fellowship PG1 DF = 14, r^2 = 0.183	-0.82	0.70	NS	-0.05	0.07	NS	-0.27	0.16	NS
Sharpaburg PG2 DF = 36, r^2 = 0.749	0.54	0.53	NS	-0.06	0.05	NS	-1.41	0.23	***
Lake Charles PG3 DF = 23, r^2 = 0.367	-3.08	1.35	*	0.19	0.10	+	-0.49	0.50	NS
Sharkey PG3 DF = 16, r^2 = 0.366	-1.26	0.63	+	-0.02	0.10	NS	-0.16	0.32	NS

Table 11. Linear regression analysis of unconfined compressive strengths of soils treated with sulfate waste (as a function of moisture content, curing time, and sulfate waste content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class IV Soils: Plasticity Index > 20, Montmorrillonitic (continued)									
Sharpsburg PG3 DF = 36, r^2 = 0.186	-0.72	0.50	NS	-0.02	0.06	NS	-0.24	0.16	NS
Sharpsburg FG2 DF = 55, r^2 = 0.341	0.62	0.50	NS	-0.01	0.07	NS	-0.49	0.23	*
Summit FG2 DF = 34, r^2 = 0.237	1.93	0.62	**	-0.01	0.09	NS	1.32	0.44	**
Sharpsburg AMD DF = 36, r^2 = 0.539	0.52	0.50	NS	-0.03	0.05	NS	-1.01	0.26	***

Key:

DF = Degrees of Freedom (number of specimens - 4)
r^2 = Index of determination (square of correlation coefficient)
*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 90% level
NS = Significance below 90% level

Sulfate Wastes (SW):

PG1 = Phosphogypsum (Florida)
PG2 = Phosphogypsum (North Carolina)
PG3 = Phosphogypsum (Texas)
FG1 = Flue Gas Desulfurization Solids (Illinois)
FG2 = Flue Gas Desulfurization Solids (Kansas)
AMD = Acid Mine Drainage Neutralization Solids (Pennsylvania)

1 psi = 6.9 kPa

Table 12. Linear regression analysis of unconfined compressive strengths of soils treated with lime (as a function of moisture content, curing time, and lime content). Linear regression coefficients, standard deviations, and statistical significances.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, % L.		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class I Soils: Plasticity Index NP-10									
Charlton - Lime DF = 3, r^2 = 0.907	-6.22	1.51	*	-0.01	0.07	ns	-3.41	0.76	*
Convent - Lime DF = 10, r^2 = 0.832	4.17	1.92	+	0.48	0.11	**	3.17	0.66	***
Coxville - Lime DF = 6, r^2 = 0.710	-4.27	5.76	ns	0.27	0.21	ns	2.96	1.63	ns
Hazelton - Lime DF = 11, r^2 = 0.865	-3.33	1.99	ns	0.04	0.09	ns	2.33	0.40	***
Manor - Lime DF = 10, r^2 = 0.777	-2.33	1.60	ns	0.27	0.17	ns	3.42	0.68	***
Norfolk - Lime DF = 7, r^2 = 0.957	23.80	7.19	*	1.34	0.22	***	8.08	0.78	***
Prentiss - Lime DF = 18, r^2 = 0.921	-3.02	1.85	+	0.07	0.07	ns	3.41	0.32	***
Class II Soils: Plasticity Index 10-25									
Commerce - Lime DF = 18, r^2 = 0.870	2.24	1.46	ns	0.17	0.08	*	3.13	0.46	***
Exum - Lime DF = 7, r^2 = 0.902	-20.69	9.72	+	0.73	0.40	ns	13.98	2.76	**
Mahoning - Lime DF = 18, r^2 = 0.239	-0.53	1.22	ns	-0.14	0.12	ns	0.95	0.59	ns
Memphis - Lime DF = 4, r^2 = 0.600	-13.19	8.25	ns	0.92	0.78	ns	0.42	0.89	ns
Miami - Lime DF = 14, r^2 = 0.611	3.66	3.76	ns	0.36	0.25	ns	4.68	1.46	**
Sassafras - Lime DF = 11, r^2 = 0.936	-2.51	0.52	***	-0.15	0.14	ns	6.05	0.50	***
Shelby - Lime DF = 15, r^2 = 0.643	-6.32	1.52	***	0.15	0.14	ns	0.68	0.56	ns
Tama - Lime DF = 22, r^2 = 0.341	-3.42	2.08	ns	0.15	0.17	ns	1.02	0.88	ns
Wharton - Lime DF = 10, r^2 = 0.588	-4.03	1.45	*	-0.11	0.14	ns	0.03	0.73	ns

Table 12. Linear regression analysis of unconfined compressive strengths of soils treated with lime (as a function of moisture content, curing time, and lime content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, % L		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic									
Chobee - Lime DF = 6, r^2 = 0.941	-0.28	2.19	ns	0.40	0.20	+	5.74	0.67	***
Craven - Lime DF = 7, r^2 = 0.904	-31.68	13.81	+	1.25	0.57	+	9.44	2.17	**
Higginsville - Lime DF = 13, r^2 = 0.431	3.39	1.62	+	-0.23	0.19	ns	2.09	0.76	*
Katy - Lime DF = 13, r^2 = 0.745	2.77	3.16	ns	-0.01	0.21	ns	4.59	0.91	***
Upshur - Lime DF = 5, r^2 = 0.802	-1.08	1.21	ns	-0.22	0.07	*	-0.54	0.64	ns
Class IV Soils: Plasticity Index > 20, Montmorillonitic									
Fellowship - Lime DF = 7, r^2 = 0.768	0.00	2.36	ns	0.05	0.10	ns	-1.63	0.38	**
Sharkey - Lime DF = 6, r^2 = 0.935	0.58	1.37	ns	0.32	0.13	*	-3.86	0.83	**
Sharpsburg - Lime DF = 30, r^2 = 0.240	1.67	0.88	+	0.08	0.09	ns	-0.43	0.47	ns
Summit - Lime DF = 12, r^2 = 0.117	-0.92	2.22	ns	0.16	0.14	ns	-0.96	1.62	ns

Key:

DF = Degrees of Freedom (number of specimens - 4)
r^2 = Index of determination (square of correlation coefficient)
*** = Significant of 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
ns = Significance below 90% level

Additive:

Lime = Hydrated lime, 90%

1 psi = 6.9 kPa

Table 13. Linear regreaaion analysis of unconfined compressive atrengths of aoils treated with sulfate waste and lime (aa a function of moisture content, curing time, lime content, and sulfate waste content). Linear regresaion coefficients, standard deviationa, and statistical significances.

System	Moiature, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficicnt	Standard Deviation	Signifi-cance	Regresaion Coefficient	Standard Deviation	Signifi-cance
Class I Soils: Plasticity Index NP-10												
Convent PG1 - Lime DF = 34, r^2 = 0.707	7.55	7.73	NS	2.19	0.33	***	4.69	2.88	NS	2.91	1.71	NS
Norfolk PG1 - Lime DF = 20, r^2 = 0.741	-4.80	1.05	***	1.09	0.27	***	8.34	1.39	***	-1.32	0.71	+
Coxville PG2 - Lime DF = 38, r^2 = 0.517	-5.59	1.95	**	0.31	0.32	NS	8.98	1.54	***	2.34	0.92	*
Prentiss PG3 - Lime DF = 68, r^2 = 0.671	-0.04	1.16	NS	0.16	0.15	NS	6.30	0.57	***	0.57	0.52	NS
Charlton FG1 - Lime DF = 13, r^2 = 0.859	-1.71	1.06	NS	0.00	0.08	NS	-0.66	1.36	NS	2.18	0.43	***
Hazelton FG1 - Lime DF = 40, r^2 = 0.506	-1.20	2.16	NS	-0.05	0.20	NS	5.66	1.21	***	2.65	0.71	***
Manor FG1 - Lime DF = 37, r^2 = 0.545	-2.60	1.91	NS	0.16	0.14	NS	2.90	0.99	**	2.90	0.73	***
Hazelton AMD - Lime DF = 40, r^2 = 0.536	-0.26	0.33	NS	-0.11	0.06	+	2.14	0.38	***	-0.08	0.22	NS
Manor AMD - Lime DF = 33, r^2 = 0.649	-1.51	0.72	*	0.20	0.07	**	2.89	0.49	***	0.66	0.24	**
Class II Soils: Plasticity Index 10-25												
Commerce PG1 - Lime DF = 43, r^2 = 0.710	-3.82	2.38	NS	1.63	0.24	***	0.79	1.40	NS	4.44	0.92	***
Memphia PG1 - Lime DF = 11, r^2 = 0.856	-15.58	9.15	NS	0.73	0.85	NS	7.92	4.14	+	11.56	3.12	**
Exum PG2 - Lime DF = 38, r^2 = 0.553	-9.43	4.89	+	2.88	0.79	***	23.29	4.21	***	5.18	2.63	+

Table 13. Linear regression analysis of unconfined compressive strengths of soils treated with sulfate waste and lime (as a function of moisture content, curing time, lime content, and sulfate waste content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class II Soils: Plasticity Index 10-25 (continued)												
Mahoning PG3 - Lime DF = 67, r^2 = 0.524	-1.23	0.64	+	0.19	0.12	NS	3.37	0.51	***	0.68	0.28	*
Tama PG3 - Lime DF = 73, r^2 = 0.570	-3.87	1.36	**	0.23	0.15	NS	4.74	0.60	***	1.29	0.41	**
Mahoning FG1 - Lime DF = 47, r^2 = 0.463	-2.45	2.22	NS	-0.20	0.11	+	0.02	1.68	NS	1.75	0.59	**
Miami, FG1 - Lime DF = 36, r^2 = 0.503	-3.17	1.30	*	-0.05	0.12	NS	2.54	0.85	**	1.77	0.55	**
Sassafras FG1 - Lime DF = 39, r^2 = 0.681	-3.25	0.93	**	-0.06	0.16	NS	7.07	0.89	***	1.58	0.39	***
Tama FG1 - Lime DF = 46, r^2 = 0.480	0.95	0.21	***	0.02	0.08	NS	2.16	0.49	***	-0.63	0.17	***
Wharton FG1 - Lime DF =35, r^2 = 0.647	-5.46	0.97	***	-0.11	0.09	NS	-0.50	0.72	NS	1.90	0.25	***
Shelby FG2 - Lime DF = 58, r^2 = 0.675	-9.25	0.92	***	0.25	0.08	**	0.79	0.47	+	-2.64	0.33	***
Mahoning AMD - Lime DF = 49, r^2 = 0.365	-0.20	0.57	NS	-0.12	0.07	+	0.58	0.42	NS	-0.71	0.22	**
Sassafras AMD - Lime DF = 38, r^2 = 0.617	-2.47	0.72	**	0.04	0.13	NS	4.32	0.71	***	0.45	0.38	NS
Shelby AMD - Lime DF = 47, r^2 = 0.116	0.74	1.22	NS	0.02	0.11	NS	0.36	0.71	NS	-0.52	0.25	*
Tama AMD - Lime DF = 54, r^2 = 0.367	-1.51	0.41	***	0.06	0.09	NS	1.01	0.57	+	-0.17	0.25	NS
Wharton AMD - Lime DF = 38, r^2 = 0.141	0.53	0.67	NS	0.04	0.08	NS	0.71	0.61	NS	-0.39	0.23	+
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic												
Chobee PG1 - Lime DF = 22, r^2 = 0.781	-6.09	1.85	**	0.21	0.22	NS	5.22	0.78	***	-0.64	0.51	NS
Craven PG2 - Lime DF = 39, r^2 = 0.791	-11.77	2.19	***	0.57	0.27	*	11.84	1.07	***	-2.16	0.69	**

Table 13. Linear regression analysis of unconfined compressive strengths of soils treated with sulfate waste and lime (as a function of moisture content, curing time, lime content, and sulfate waste content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic (continued)												
Katy PG3 - Lime DF = 64, r^2 = 0.609	-3.56	0.71	***	0.34	0.19	+	4.89	0.71	***	-0.89	0.43	*
Higginsville FG1 - Lime DF = 34, r^2 = 0.113	-1.03	1.23	NS	-0.04	0.14	NS	1.45	0.87	NS	0.19	0.32	NS
Upshur FG1 - Lime DF = 11, r^2 = 0.783	-8.35	1.76	***	0.05	0.11	NS	-1.25	1.22	NS	-1.27	0.42	*
Higginsville FG2 - Lime DF = 43, r^2 = 0.072	-0.57	1.03	NS	-0.21	0.15	NS	0.14	0.84	NS	0.07	0.45	NS
Class IV Soils: Plasticity Index > 20, Montmorillonitic												
Fellowship PG1 - Lime DF = 36, r^2 = 0.517	0.25	0.23	NS	-0.50	0.09	***	-1.47	0.47	**	0.02	0.23	NS
Sharkey PG1 - Lime DF = 9, r^2 = 0.752	1.92	2.42	NS	0.42	0.21	+	-3.03	1.46	+	0.07	0.90	NS
Sharpsburg PG2 - Lime DF = 62, r^2 = 0.450	-4.33	1.96	*	0.59	0.21	**	3.11	1.07	**	2.10	0.81	*
Sharkey PG3 - Lime DF = 35, r^2 = 0.248	0.62	1.52	NS	0.23	0.27	NS	1.08	1.07	NS	1.75	1.04	NS
Sharpsburg PG3 - Lime DF = 62, r^2 = 0.179	-0.96	1.17	NS	0.29	0.15	+	1.78	0.69	*	0.18	0.42	NS
Sharpsburg FG1 - Lime DF = 56, r^2 = 0.128	1.17	0.70	NS	0.05	0.06	NS	-0.69	0.18	***	-0.29	0.19	NS
Sharpsburg FG2 - Lime DF = 81, r^2 = 0.191	1.81	0.50	***	0.04	0.07	NS	0.26	0.43	NS	0.18	0.20	NS
Summit FG2 - Lime DF = 54, r^2 = 0.130	0.50	0.64	NS	0.17	0.09	+	-0.75	0.67	NS	0.12	0.41	NS
Sharpsburg AMD - Lime DF = 61, r^2 = 0.657	2.23	0.60	***	0.12	0.06	*	-0.78	0.47	NS	-1.99	0.24	***

Key:

DF = Degrees of Freedom (number of specimens - 5)
r^2 = Index of Determination (square of correlation coefficient)
*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
NS = Significant below 90% level

Additive:
Lime = Hydrated Lime, 90%

Sulfate Wastes:
PG1 = Phosphogypsum (Florida)
PG2 = Phosphogypsum (North Carolina)
PG3 = Phosphygypsum (Texas)
FG1 = Flue Gas Desulfurization Solids (Illinois)
FG2 = Flue Gas Desulfurization Solids (Kansas)
AMD = Acid Mine Drainage Neutralization Solids (Pennsylvania)

1 psi = 6.9 kPa

Table 14. Linear regression analysis of unconfined compressive strengths of soils treated with lime, phosphogypsum, and fly ash (as a function of moisture content, curing time, lime content, phosphogypsum content, and fly ash content). Linear regression coefficients, standard deviations, and statistical significances.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance
Class I Soils: Plasticity Index NP-10															
Coxville PC2-Lime DF = 38, r^2 = 0.517	-5.59	1.95	**	0.31	0.32	ns	8.98	1.54	***	2.34	0.92	*	--	--	--
Coxville PG2-Lime-FA DF = 61, r^2 = 0.802	-8.90	2.13	***	0.49	0.35	ns	10.67	1.63	***	2.88	1.07	**	16.38	1.22	***
Prentiss PC3-Lime DF = 68, r^2 = 0.671	-0.04	1.16	ns	0.16	0.15	ns	6.30	0.57	***	0.57	0.52	ns	--	--	--
Prentiss PC3-Lime-FA DF = 91, r^2 = 0.634	-3.78	2.16	+	0.59	0.27	*	6.71	1.07	***	0.75	1.02	ns	8.09	1.11	***
Class II Soils: Plasticity Index 10-25															
Commerce PC1-Lime DF = 43, r^2 = 0.710	-3.82	2.38	ns	1.63	0.24	***	0.79	1.40	ns	4.44	0.92	***	--	--	--
Commerce PC1-Lime-FA DF = 65, r^2 = 0.671	-2.03	2.57	ns	1.60	0.22	***	3.66	1.31	**	2.54	0.97	*	5.10	0.85	***
Mahoning PC3-Lime DF = 67, r^2 = 0.524	-1.23	0.64	+	0.19	0.12	ns	3.37	0.51	***	0.68	0.28	*	--	--	--
Mahoning PG3-Lime-FA DF = 90, r^2 = 0.720	-1.52	0.75	*	0.17	0.14	ns	3.79	0.57	***	0.22	0.34	ns	5.28	0.58	***
Class III Soils: Plasticity Index > 25, Nonmontmorillonitic															
Craven PC2-Lime DF = 39, r^2 = 0.791	-11.77	2.19	***	0.57	0.27	*	11.84	1.07	***	-2.16	0.69	**	--	--	--
Craven PG2-Lime-FA DF = 62, r^2 = 0.841	-16.44	2.38	***	0.69	0.28	*	15.17	1.44	***	1.96	0.75	*	11.69	1.26	***
Katy PG3-Lime DF = 64, r^2 = 0.609	-3.56	0.71	***	0.34	0.19	+	4.89	0.71	***	-0.89	0.43	*	--	--	--
Katy PG3-Lime-FA DF = 87, r^2 = 0.727	-1.05	1.10	ns	0.29	0.25	ns	8.00	1.02	***	-1.28	0.66	+	8.71	1.05	***

Table 14. Linear regression analysis of unconfined compressive strengths of soils treated with lime, phosphogypsum, and fly ash (as a function of moisture content, curing time, lime content, phosphogypsum content, and fly ash content). Linear regression coefficients, standard deviations, and statistical significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance	Regression Coefficient	Std. Dev.	Signi-ficance
Class IV Soils: Plasticity Index > 20, Montmorillonitic															
Fellowship PG1-Lime DF = 36, r^2 = 0.517	0.25	0.23	ns	-0.50	0.09	***	-1.47	0.47	**	0.02	0.23	ns	--	--	--
Fellowship PG1-Lime-FA DF = 57, r^2 = 0.309	-0.44	0.27	ns	-0.46	0.10	***	0.63	0.51	ns	0.38	0.31	ns	-0.60	0.44	ns
Sharpsburg PG2-Lime DF = 62, r^2 = 0.450	-4.33	1.96	*	0.59	0.21	**	3.11	1.07	**	2.10	0.81	*	--	--	--
Sharpsburg PG2-Lime-FA DF = 84, r^2 = 0.485	-2.84	1.56	+	0.40	0.17	*	4.27	0.88	***	1.51	0.68	*	0.54	0.71	ns

Key:

DF = Degrees of Freedom (number of specimens - 5, for lime/phosphogypsum-treated systems; number of specimens - 6, for lime/phosphogypsum/fly ash-treated systems)
r^2 = Index of determination (square of correlation coefficient)
*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
ns = Significance below 90% level

Additives:

Lime = Hydrated lime, 90%
FA = Fly Ash (Missouri)

Sulfate Wastes:

PG1 = Phosphogypsum (Florida)
PG2 = Phosphogypsum (North Carolina)
PG3 = Phsophogypsum (Texas)

1 psi = 6.9 kPa

Table 15. Linear regression analysis of unconfined compressive strengths of soils treated with portland cement and phosphogypsum (as a function of moisture content, curing time, cement content, and phosphogypsum content). Linear regression coefficients, standard deviations, and statistical significances.

System	Moisture, PSI/% H_2O			Time, PSI/day			Cement, PSI/% C			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class I Soils: Plasticity Index NP-10												
Delray - Cement DF = 6, r^2 = 0.983	-8.77	1.86	**	0.06	0.06	NS	-4.85	1.69	*	-	-	-
Delray - PG1 - Cement DF = 20, r^2 = 0.740	-0.06	0.38	NS	0.13	0.09	NS	1.74	0.34	***	-0.28	0.17	NS
Kendrick - Cement DF = 3, r^2 = 0.974	0.00	-	NS	0.13	0.12	NS	39.83	4.49	***	-	-	-
Kendrick PG1 - Cement DF = 17, r^2 = 0.852	18.76	9.01	+	1.81	1.25	NS	41.45	4.69	***	-8.77	3.81	*
Norfolk - Cement DF = 5, r^2 = 0.978	-58.30	40.97	NS	2.90	1.47	NS	35.68	9.17	*	-	-	-
Norfolk - PG1 - Cement DF = 13, r^2 = 0.763	-30.16	13.46	*	1.46	2.05	NS	43.33	9.38	***	-1.42	5.85	NS
Class IV Soils: Plasticity Index > 20, Montmorillonitic												
Fellowship - Cement DF = 5, r^2 = 0.700	-8.77	5.07	NS	-0.35	0.23	NS	-0.99	2.09	NS	-	-	-
Fellowship PG1 - Cement DF = 24, r^2 = 0.447	-4.86	2.22	*	-0.48	0.24	+	1.14	1.16	NS	-1.01	0.53	+

Key:

DF = Degrees of Freedom (number of specimens - 4, for cement-treated systems; number of specimens - 5, for cement/phosphogypsum-treated systems)
r^2 = Index of determination (square of correlation coefficient)
*** = Significant at 99.9% level
** = Significant at 99% level
* = Significant at 95% level
+ = Significant at 90% level
NS = Significant below 90% level

Additive:

Cement = Portland Cement, Type I

Sulfate Waste:

PG1 = Phosphogypsum (Florida)

1 psi = 6.9 kPa

Table 16. Linear regression analysis of unconfined compressive strengths of soils treated with cement kiln dust and sulfate waste (as a function of moisture content, curing time, kiln dust content, and sulfate waste content). Linear regression coefficients, standard deviations, and statistical significances.

System	Moisture, PSI/% H_2O			Time, PSI/day			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Class I Soils: Plasticity Index NP-10												
Hazelton - KD DF = 12, r^2 = 0.885	-3.85	1.78	+	-0.12	0.07	NS	0.95	0.50	+	-	-	-
Hazelton AMD - KD DF = 45, r^2 = 0.817	-0.86	0.54	NS	-0.11	0.09	NS	3.23	0.41	***	0.77	0.30	*
Manor - KD DF = 6, r^2 = 0.953	-8.50	4.34	+	0.32	0.20	NS	5.89	0.93	***	-	-	-
Manor AMD - KD DF = 40, r^2 = 0.853	-3.35	1.05	**	0.07	0.09	NS	4.33	0.34	***	0.40	0.32	NS
Claas II Soils: Plasticity Index 10-25												
Mahoning - KD DF = 17, r^2 = 0.726	-0.80	1.69	NS	-0.22	0.17	NS	4.40	0.90	***	-	-	-
Mahoning AMD - KD DF = 53, r^2 = 0.956	3.41	0.20	***	-0.48	0.04	***	4.34	0.13	***	-0.83	0.08	***
Shelby - KD DF = 15, r^2 = 0.887	-5.62	1.55	**	0.07	0.14	NS	3.51	0.67	***	-	-	-
Shelby FG2 - KD DF = 65, r^2 = 0.868	-3.80	0.69	***	0.12	0.11	NS	5.74	0.35	***	-0.18	0.29	NS
Wharton - KD DF = 6, r^2 = 0.913	8.68	6.58	NS	-0.42	0.19	+	9.35	3.87	+	-	-	-
Wharton AMD - KD DF = 42, r^2 = 0.487	-0.49	0.59	NS	-0.11	0.11	NS	1.96	0.41	***	-0.06	0.04	NS

1 psi = 6.9 kPa

Tsble 16. Linesr regression anslysis of unconfined compressive strengths of soils trested with cement kiln dust and sulfate wsste (as a function of moisture content, curing time, kiln dust content, snd sulfate wsste content). Linear regression coefficients, stsndard deviations, and statisticsl significances (continued).

System	Moisture, PSI/% H_2O			Time, PSI/day			Kiln Dust, PSI/% KD			Sulfste Waste, PSI/% SW		
	Regression Coefficient	Stsndard Deviation	Signifi-cance	Regression Cocfficient	Standsrd Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standsrd Deviation	Signifi-cance
Glass III Soils: Plasticity Index > 25, Nonmontmorillonitic												
Higginsville - KD DF = 10, r^2 = 0.957	-4.05	0.51	***	0.01	0.05	NS	-4.40	0.36	***	-	-	-
Higginsville, FG2 - KD DF = 55, r^2 = 0.740	5.61	1.42	***	0.07	0.20	NS	5.17	0.59	***	3.90	0.48	***
Glass IV Soils: Plasticity Index > 20, Montmorillonitic												
Shsrpsburg - KD DF = 27, r^2 = 0.470	0.87	0.83	NS	-0.02	0.08	NS	2.12	0.52	***	-	-	-
Shsrpsburg FG2 - KD DF = 83, r^2 = 0.998	-3.16	0.06	***	0.06	0.01	***	4.45	0.02	***	-2.44	0.02	***
Summit - KD DF = 12, r^2 = 0.673	-2.19	2.59	NS	0.04	0.19	NS	2.08	1.28	NS	-	-	-
Summit FG2 - KD DF = 61, r^2 = 0.582	2.25	1.00	*	-0.03	0.18	NS	5.50	0.63	***	1.88	0.59	**

Key:

DF = Degrees of Freedom (number of specimens - 4, for kiln dust-trested systems; number of specimens - 5, for kiln dust/sulfate waste-trested systems)
r^2 = Index of determination (square of correlation coefficient)
*** = Significsnt at 99.9% level
** = Significant at 99% level
* = Signific snt at 95% level
+ = Significant at 90% level
NS = Significsnt below 90% level

Additive:

KD = Gement Kiln Dust (Kansas)

Sulfste Wastes:

FG2 = Flue Gas Desulfurization Solids (Kansas)
AMD = Acid Minc Drainsge Neutralization Solids (Pennsylvania)

1 psi = 6.9 kPa

Table 17. Effect of vacuum saturation tests for freeze-thaw stability on unconfined compressive strength of selected soil/sulfate waste and soil/sulfate waste/lime systems.

Soil Series	Soil Class	Treatment Level	28-Day Unconfined Compressive Strength, psi (Moisture, %)	Freeze-Thaw Unconfined Compressive Strength, psi (Moisture, %)	Percent of Original Strength (Percent of Original moisture)
Mahoning	II	6% PG3	27,30,27 (24,24,24)	13,8,17 (27,26,25)	46 (108)
		6% PG3 6% Lime	24,46,85 (26,19,18)	30,28,19 (33,33,36)	50 (162)
Tama	II	6% PG3	49,37,50 (21,21,21)	5,5,6 (32,33,31)	11 (152)
		6% PG3 6% Lime	64,86,69 (27,27,24)	37,40,48 (45,46,47)	57 (184)
Wharton	II	6% AMD	42,40 (26,26)	2,3,Disintegrated (28,41,-)	7 (154)
		6% AMD 2% Lime	32,32 (22,21)	5,4,5 (33,27,27)	16 (132)
Sharpsburg	IV	6% PG2	41,40 (26,26)	4,3,Disintegrated (33,33,-)	10 (127)
		6% PG2 6% Lime	129,116,62 (23,24,27)	40,33,40 (42,42,43)	37 (168)

Table 17. Effect of vacuum saturation tests for freeze-thaw stability on unconfined compressive strength of selected soil/sulfate waste and soil/sulfate waste/lime systems (continued).

Soil Series	Soil Class	Treatment Level	28-Day Unconfined Compressive Strength, psi (Moisture, %)	Freeze-Thaw Unconfined Compressive Strength, psi (Moisture, %)	Percent of Original Strength (Percent of Original moisture)
Sharpsburg	IV	6% FG2	40,45,47 (22,22,22)	3,4,5, (53,34,34)	9 (182)
		5% FG2 2% Lime	43,49,52 (22,22,22)	28,23,28 (33,35,36)	54 (159)

Key: PG2 - Phosphogypsum (North Carolina)
PG3 - Phosphogypsum (Texas)
FG2 - Flue Gas Desulfurication Solids (Kansas)
AMD - Neutralized Acid Mine Drainage Solid (Pennsylvania)

Table 18. Shrink-swell potential of selected Sulfate waste treated soils.

Soil Series	Soil Class	Treatment Level[a/]	Expansion (%)	Shrinkage (%)	Volume Change (%)	Shrink-Swell Treated Soils[b/]	Shrink-Swell Untreated Soils[c/]
Exum	II	6% PG2	0.5	3.1	3.6	Moderate	Moderate
Mahoning	II	6% PG3	0.8	1.9	2.7	Moderate	Moderate
Shelby	II	6¢ FG2	2.3	6.8	9.1	Very High	Moderate
Katy	III	6% PG3	2.2	8 4	10.6	Very High	Moderate
Fellowship	IV	6% PG1	0.8	8.6	9.4	Very High	Not Reported
Summit	IV	6% FG2	1.6	18.2	19.8	Very High	High

a/ Key: PG1 - Phosphogypsum (Florida)
PG2 - Phosphogypsum (North CArolina)
PG3 - Phosphogypsum (Texas)
FG2 - Flue Gas Desulfurization Solids (Kansas)

b/ Soil Conservation Service, "Guide for Interpreting Engineering Uses of Soils," November 1971, pp. 14-16, Re. Shrink-Swell Potential:

Very Low: Volume Charge < 1.0%
Low: Volume Change 1-2%
Moderate: Volume Change 2-4%
High: Volume Change 4-6%
Very High: Volume Change > 6%

c/ Shrink-Swell Potential Reported in Soil Survey Interpretations.

Table 19. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Atkins series.

System	Moisture (%)			Time (days)			Sulfate Waste (%)		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 7, r^2 = 0.424	-12.76	5.85	ns	0.04	0.16	ns	-	-	-
FGl DF = 20, r^2 = 0.384	-4.19	1.82	*	-0.16	0.09	+	0.82	0.51	ns
AMD DF = 21, r^2 = 0.101	-2.64	1.75	ns	0.06	0.11	ns	1.14	0.83	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

Table 20. Linear regression coefficients, standard deviation, and statistical significances for unconfined compressive strength data: Charlton series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.898	-7.27	2.09	+	0.00	0.08	ns	-	-	-	-	-	-
Lime DF = 3, r^2 = 0.907	-6.22	1.51	*	-0.01	0.07	ns	-3.41	0.76	*	-	-	-
FGl-Lime DF = 13, r^2 = 0.859	-1.71	1.06	ns	0.00	0.08	ns	-0.66	1.36	ns	2.18	0.43	***
AMD DF = 16, r^2 = 0.244	-1.03	0.62	ns	-0.08	0.07	ns	-	-	-	0.59	0.37	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 21. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Convent series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.213	0.00	-	ns	0.11	0.15	ns	-	-	-	-	-	-
Lime DF = 10, r^2 = 0.832	4.17	1.92	+	0.48	0.11	**	3.17	0.66	***	-	-	-
PGl-Lime DF = 34, r^2 = 0.707	7.55	7.73	ns	2.19	0.33	***	4.69	2.88	ns	2.91	1.71	ns
PG3 DF = 16, r^2 = 0.169	-0.29	0.56	ns	-0.03	0.04	ns	-	-	-	-0.08	0.13	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 22. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Coxville series

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/ FA		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 1, r^2 = 0.439	4.87	6.52	ns	0.22	0.25	ns	-	-	-	-	-	-	-	-	-
Lime DF = 6, r^2 = 0.710	-4.27	5.76	ns	0.27	0.21	ns	2.96	1.63	ns	-	-	-	-	-	-
PG2 DF = 15, r^2 = 0.640	-2.57	1.49	ns	-0.04	0.07	ns	-	-	-	-0.50	0.27	+	-	-	-
PG2-Lime DF = 38, r^2 = 0.517	-5.59	1.95	**	0.31	0.32	ns	8.98	1.54	***	2.34	0.92	*	-	-	-
PG2-Lime-Fly Ash DF = 61, r^2 = 0.802	-8.90	2.13	***	0.49	0.35	ns	10.67	1.63	***	2.88	1.07	**	10.38	1.22	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 23. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Delray series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Cement, PSI/% C			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 3, r^2 = 0.200	0.00	-	ns	0.02	0.03	ns	-	-	-	-	-	-
Cement DF = 6, r^2 = 0.983	-8.77	1.86	**	0.06	0.06	ns	-4.85	1.69	*	-	-	-
PGl DF = 11, r^2 = 0.254	0.14	0.26	ns	0.00	0.03	ns	-	-	-	-0.01	0.06	ns
PGl-Cement DF = 20, r^2 = 0.740	-0.06	0.38	ns	0.13	0.09	ns	1.74	0.34	***	-0.28	0.17	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 24. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Hazelton series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 7, r^2 = 0.254	-3.02	2.19	ns	0.06	0.10	ns	-	-	-	-	-	-	-	-	-
Lime DF = 11, r^2 = 0.865	-3.33	1.99	ns	0.04	0.09	ns	2.33	0.40	***	-	-	-	-	-	-
Kiln Dust DF = 12, r^2 = 0.885	-3.85	1.78	+	-0.12	0.07	ns	-	-	-	0.95	0.50	+	-	-	-
FGl DF = 20, r^2 = 0.535	-2.23	0.47	***	0.07	0.06	ns	-	-	-	-	-	-	0.65	0.17	**
FGl-Lime DF = 40, r^2 = 0.506	-1.20	2.16	ns	-0.05	0.20	ns	5.66	1.21	***	-	-	-	2.65	0.71	***
AMD DF = 20, r^2 = 0.081	0.26	0.38	ns	-0.09	0.09	ns	-	-	-	-	-	-	-0.15	0.28	ns
AMD-Lime DF = 40, r^2 = 0.536	-0.26	0.33	ns	-0.11	0.06	+	2.14	0.38	***	-	-	-	-0.08	0.22	ns
AMD-Kiln Dust DF = 45, r^2 = 0.817	-0.86	0.54	ns	-0.11	0.09	ns	-	-	-	3.23	0.41	***	0.77	0.30	*

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 25. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Kendrick series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Cement, PSI/% C			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.762	0.00	-	ns	0.13	0.07	ns	-	-	-	-	-	-
Cement DF = 3, r^2 = 0.974	0.00	-	ns	0.13	0.12	ns	39.83	4.49	***	-	-	-
PC1 DF = 11, r^2 = 0.845	-12.24	1.65	***	0.10	0.04	*	-	-	-	2.86	0.42	***
PC1-Cement DF = 17, r^2 = 0.852	18.76	9.01	+	1.81	1.25	ns	41.45	4.69	***	-8.77	3.81	*

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 26. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Manor series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 1, r^2 = 0.183	0.46	2.95	ns	-0.05	0.14	ns	-	-	-	-	-	-	-	-	-
Lime DF = 10, r^2 = 0.777	-2.33	1.60	ns	0.27	0.17	ns	3.42	0.68	***	-	-	-	-	-	-
Kiln Dust DF = 6, r^2 = 0.953	-8.50	4.34	+	0.32	0.20	ns	-	-	-	5.89	0.93	***	-	-	-
FGl-Lime DF = 37, r^2 = 0.545	-2.60	1.91	ns	0.16	0.14	ns	2.90	0.99	**	-	-	-	2.90	0.73	***
AMD DF = 13, r^2 = 0.176	-1.19	0.62	+	0.12	0.07	ns	-	-	-	-	-	-	0.98	0.18	***
AMD-Lime DF = 33, r^2 = 0.649	-1.51	0.72	*	0.20	0.07	**	2.89	0.49	***	-	-	-	0.66	0.24	**
AMD-Kiln Dust DF = 40, r^2 = 0.853	-3.35	1.05	**	0.07	0.09	ns	-	-	-	4.33	0.34	***	0.40	0.32	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 34. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Miami series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 6, r^2 = 0.047	1.16	2.13	ns	-0.05	0.18	ns	-	-	-	-	-	-
Lime DF = 14, r^2 = 0.611	3.66	3.76	ns	0.36	0.25	ns	4.68	1.46	**	-	-	-
PG2 DF = 20, r^2 = 0.513	-0.60	0.77	ns	-0.02	0.08	ns	-	-	-	-0.64	0.34	+
FGl-Lime DF = 36, r^2 = 0.503	-3.17	1.30	*	-0.05	0.12	ns	2.54	0.85	**	1.77	0.55	**
AMD DF = 17, r^2 = 0.299	-0.88	0.69	ns	0.14	0.10	ns	-	-	-	-0.03	0.39	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 33. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Memphis series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.791	-8.18	3.00	+	0.00	0.13	ns	-	-	-	-	-	-
Lime DF = 4, r^2 = 0.600	-13.19	8.25	ns	0.92	0.78	ns	0.42	0.89	ns	-	-	-
PGl-Lime DF = 11, r^2 = 0.856	-15.58	9.15	ns	0.73	0.85	ns	7.92	4.14	+	11.56	3.12	**
PG3 DF = 16, r^2 = 0.699	-0.44	0.82	ns	-0.04	0.07	ns	-	-	-	-0.99	0.23	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 619 kPa

Table 32. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Mahoning series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% PA		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 13, r^2 = 0.288	-0.87	1.07	ns	-0.28	0.12	*	-	-	-	-	-	-	-	-	-	-	-	-
Lime DF = 18, r^2 = 0.239	-0.53	1.22	ns	-0.14	0.12	ns	0.95	0.59	ns	-	-	-	-	-	-	-	-	-
Kiln Dust DF = 17, r^2 = 0.726	-0.80	1.69	ns	-0.22	0.17	ns	-	-	-	4.40	0.90	***	-	-	-	-	-	-
PG3 DF = 45, r^2 = 0.065	-0.78	0.48	ns	0.07	0.10	ns	-	-	-	-	-	-	-0.11	0.22	ns	-	-	-
PG3-Lime DF = 67, r^2 = 0.524	-1.23	0.64	+	0.19	0.12	ns	3.37	0.51	***	-	-	-	0.68	0.28	*	-	-	-
PG3-Lime-Fly Ash DF = 90 r^2 = 0.720	-1.52	0.75	*	0.17	0.14	ns	3.79	0.57	***	-	-	-	0.22	0.34	ns	5.28	0.58	***
FGI DF = 16, r^2 = 0.453	-0.98	0.93	ns	-0.26	0.10	*	-	-	-	-	-	-	-1.04	0.46	*	-	-	-
FGI-Lime DF = 47, r^2 = 0.463	-2.45	2.22	ns	-0.20	0.11	+	0.02	1.68	ns	-	-	-	1.75	0.59	**	-	-	-
AMD DF = 27, r^2 = 0.503	-1.75	0.71	*	-0.25	0.07	**	-	-	-	-	-	-	0.11	0.27	ns	-	-	-
AMD-Lime DF = 49, r^2 = 0.365	-0.20	0.57	ns	-0.12	0.07	+	0.58	0.42	ns	-	-	-	-0.71	0.22	**	-	-	-
AMD-Kiln Dust DF = 53, r^2 = 0.956	3.41	0.20	***	-0.48	0.04	***	-	-	-	4.34	0.13	***	-0.83	0.08	***	-	-	-

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 31. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Exum series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.863	-3.07	0.89	+	-0.04	0.03	ns	-	-	-	-	-	-
Lime DF = 7, r^2 = 0.902	-20.69	9.72	+	0.73	0.40	ns	13.98	2.76	**	-	-	-
PG2 DF = 16, r^2 = 0.598	-2.15	1.10	+	-0.05	0.05	ns	-	-	-	-0.20	0.22	ns
PG2-Lime DF = 38, r^2 = 0.553	-9.43	4.89	+	2.88	0.79	***	23.29	4.21	***	5.18	2.63	+

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 30. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Commerce series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 7, r^2 = 0.100	0.00	-	ns	0.08	0.09	ns	-	-	-	-	-	-	-	-	-
Lime DF = 18, r^2 = 0.870	2.24	1.46	ns	0.17	0.08	*	3.13	0.46	***	-	-	-	-	-	-
PGl-Lime DF = 43, r^2 = 0.710	-3.82	2.38	ns	1.63	0.24	***	0.79	1.40	ns	4.44	0.92	***	-	-	-
PGl-Lime-Fly Ash DF = 65, r^2 = 0.671	-2.03	2.57	ns	1.60	0.22	***	3.66	1.31	**	2.54	0.97	*	5.10	0.85	***
PG3 DF = 44, r^2 = 0.130	-1.33	1.60	ns	0.02	0.06	ns	-	-	-	0.54	0.30	+	-	-	-

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 29. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Wagram series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 1, r^2 = 0.999	-2.71	6.00	ns	0.29	0.60	ns	-	-	-
PG2 DF = 14, r^2 = 0.828	-1.08	0.69	ns	-0.03	0.02	ns	0.74	0.22	**

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 28. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Prentiss series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 13, r^2 = 0.090	-2.45	2.94	ns	-0.01	0.11	ns	-	-	-	-	-	-	-	-	-
Lime DF = 18, r^2 = 0.921	-3.02	1.85	+	0.07	0.07	ns	3.41	0.32	***	-	-	-	-	-	-
PG2 DF = 25, r^2 = 0.248	-3.83	1.63	*	0.07	0.06	ns	-	-	-	0.65	0.37	+	-	-	-
PG3 DF = 45, r^2 = 0.116	-0.04	0.50	ns	-0.06	0.04	ns	-	-	-	0.11	0.15	ns	-	-	-
PG3-Lime DF = 68, r^2 = 0.671	-0.04	1.16	ns	0.16	0.15	ns	6.30	0.57	***	0.57	0.52	ns	-	-	-
PG3-Lime-Fly Ash DF = 91, r^2 = 0.634	-3.78	2.16	+	0.59	0.27	*	6.71	1.07	***	0.75	1.02	ns	8.09	1.11	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 27. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Norfolk series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Cement, PSI/% C			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.987	3.08	0.61	*	0.27	0.03	*	-	-	-	-	-	-	-	-	-
Lime DF = 7, r^2 = 0.957	23.80	7.19	*	1.34	0.22	***	8.08	0.78	***	-	-	-	-	-	-
Cement OF = 5, r^2 = 0.978	-58.30	40.97	ns	2.90	1.47	ns	-	-	-	35.68	9.17	*	-	-	-
PG1-Lime DF = 20, r^2 = 0.741	-4.80	1.05	***	1.09	0.27	***	8.34	1.39	***	-		-	-1.32	0.71	+
PG1-Cement OF = 13, r^2 = 0.763	-30.16	13.46	*	1.46	2.05	ns	-	-	-	43.33	9.38	***	-1.42	5.85	ns
PG2 OF = 16, r^2 = 0.642	-3.66	0.70	***	0.03	0.12	ns	-	-	-	-	-	-	0.33	0.13	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 35. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Sassafras series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 6, r^2 = 0.812	-6.04	1.60	**	-0.21	0.13	ns	-	-	-	-	-	-
Lime DF = 11, r^2 = 0.936	-2.51	0.52	***	-0.15	0.14	ns	6.05	0.50	***	-	-	-
FGl DF = 17, r^2 = 0.453	-2.35	1.35	+	-0.37	0.11	**	-	-	-	0.76	0.32	*
FGl-Lime DF = 39, r^2 = 0.681	-3.25	0.93	***	-0.06	0.16	ns	7.07	0.89	***	1.58	0.39	***
AMD DF = 19, r^2 = 0.605	-7.12	1.42	***	-0.04	0.12	ns	-	-	-	3.25	0.61	***
AMD-Lime DF = 38, r^2 = 0.617	-2.47	0.72	**	0.04	0.13	ns	4.32	0.71	***	0.45	0.38	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 36. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Shelby series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 10, r^2 = 0.510	-4.92	1.55	**	-0.02	0.16	ns	-	-	-	-	-	-	-	-	-
Lime DF = 15, r^2 = 0.643	-6.32	1.52	***	0.15	0.14	ns	0.68	0.56	ns	-	-	-	-	-	-
Kiln Dust DF = 15, r^2 = 0.887	-5.62	1.55	**	0.07	0.14	ns	-	-	-	3.51	0.67	***	-	-	-
FG2 DF = 37, r^2 = 0.693	-7.32	0.82	***	-0.02	0.07	ns	-	-	-	-	-	-	-2.11	0.29	***
FG2-Lime DF = 58, r^2 = 0.675	-9.25	0.92	***	0.25	0.08	**	0.79	0.47	+	-	-	-	-2.64	0.33	***
FG2-Kiln Dust DF = 65, r^2 = 0.868	-3.80	0.69	***	0.12	0.11	ns	-	-	-	5.74	0.35	***	-0.18	0.29	ns
AMD DF = 24, r^2 = 0.169	-4.78	1.77	*	0.05	0.10	ns	-	-	-	-	-	-	0.69	0.23	**
AMD-Lime DF = 47, r^2 = 0.116	0.74	1.22	ns	0.02	0.11	ns	0.36	0.71	ns	-	-	-	-0.52	0.25	*

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 37. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Tama series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/day SW		
	Regresaion Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance
Control DF = 14, r^2 = 0.012	-0.54	1.52	ns	-0.03	0.13	ns	-	-	-	-	-	-
Lime DF = 22, r^2 = 0.341	-3.42	2.08	ns	0.15	0.17	ns	1.02	0.88	ns	-	-	-
PG3 DF = 47, r^2 = 0.238	-0.70	0.84	ns	-0.16	0.08	+	-	-	-	-0.45	0.23	+
PG3-Lime DF = 73, r^2 = 0.570	-3.87	1.36	**	0.23	0.15	ns	4.74	0.60	***	1.29	0.41	**
FGl-Lime DF = 46, r^2 = 0.480	0.95	0.21	***	0.02	0.08	ns	2.16	0.49	***	-0.63	0.17	***
AMD DF = 28, r^2 = 0.123	-0.95	0.30	**	-0.06	0.09	ns	-	-	-	-0.18	0.20	ns
AMD-Lime DF = 54, r^2 = 0.367	-1.51	0.41	***	0.06	0.09	ns	1.01	0.57	+	-0.17	0.25	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 38. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Wharton series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 1, r^2 = 0.155	-4.73	12.09	ns	0.23	0.54	ns	-	-	-	-	-	-	-	-	-
Lime DF = 10, r^2 = 0.588	-4.03	1.45	*	-0.11	0.14	ns	0.03	0.73	ns	-	-	-	-	-	-
Kiln Dust DF = 6, r^2 = 0.913	8.68	6.58	ns	-0.42	0.19	+	-	-	-	9.35	3.87	+	-	-	-
FGl-Lime DF = 35, r^2 = 0.647	-5.46	0.97	***	-0.11	0.09	ns	-0.50	0.72	ns	-	-	-	1.90	0.25	***
AMD DF = 13, r^2 = 0.615	0.24	0.79	ns	0.14	0.07	+	-	-	-	-	-	-	0.79	0.21	**
AMD-Lime DF = 38, r^2 = 0.141	0.53	0.67	ns	0.04	0.08	ns	0.71	0.61	ns	-	-	-	-0.39	0.23	+
AMD-Kiln Dust DF = 42, r^2 = 0.487	-0.49	0.59	ns	-0.11	0.11	ns	-	-	-	1.96	0.41	***	-0.06	0.04	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 39. Linear regression coefficients, standard deviation, and statistical significance for unconfined compressive atrength data: Chobee series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance
Control DF = 3, r^2 = 0.895	2.00	1.15	ns	0.30	0.08	*	-	-	-	-	-	-
Lime DF = 6, r^2 = 0.941	-0.28	2.19	ns	0.40	0.20	+	5.74	0.67	***	-	-	-
PGl DF = 14, r^2 = 0.821	-4.02	1.05	**	-0.11	0.09	ns	-	-	-	-0.37	0.20	+
PGl-Lime DF = 22, r^2 = 0.781	-6.09	1.85	**	0.21	0.22	ns	5.22	0.78	***	-0.64	0.51	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient)
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPs

Table 40. Linear regression coefficients, standard deviations, and statistical significance for unconfined compressive strength data: Craven series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.170	-2.89	5.27	ns	0.06	0.19	ns	-	-	-	-	-	-	-	-	-
Lime DF = 7, r^2 = 0.904	-31.68	13.81	+	1.25	0.57	+	9.44	2.17	**	-	-	-	-	-	-
PG2 DF = 16, r^2 = 0.709	-3.98	0.77	***	-0.05	0.08	ns	-	-	-	-1.23	0.22	***	-	-	-
PG2-Lime DF = 39, r^2 = 0.791	-11.77	2.19	***	0.57	0.27	*	11.84	1.07	***	-2.16	0.69	**	-	-	-
PG2-Lime-Fly Ash DF = 62, r^2 = 0.841	-16.44	2.38	***	0.69	0.28	*	15.17	1.44	***	1.96	0.75	*	11.69	1.26	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 41. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Hartwell series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 9, r^2 = 0.377	-5.06	2.21	*	0.22	0.20	ns	-	-	-
FG2 DF = 42, r^2 = 0.656	-2.64	0.50	***	0.37	0.01	***	-0.62	0.17	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 42. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Higginsville series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KO			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 5, r^2 = 0.107	2.39	5.88	ns	-0.22	0.30	ns	-	-	-	-	-	-	-	-	-
Lime DF = 13, r^2 = 0.431	3.39	1.62	+	-0.23	0.19	ns	2.09	0.76	*	-	-	-	-	-	-
Kiln Dust DF = 10, r^2 = 0.957	-4.05	0.51	***	0.01	0.05	ns	-	-	-	-4.40	0.36	***	-	-	-
FGl-Lime DF = 34, r^2 = 0.113	-1.03	1.23	ns	-0.04	0.14	ns	1.45	0.87	ns	-	-	-	0.19	0.32	ns
FG2 DF = 26, r^2 = 0.283	-1.59	1.15	ns	-0.11	0.13	ns	-	-	-	-	-	-	0.15	0.50	ns
FG2-Lime DF = 43, r^2 = 0.072	-0.57	1.03	ns	-0.21	0.15	ns	0.14	0.84	ns	-	-	-	0.07	0.45	ns
FG2-Kiln Dust DF = 55, r^2 = 0.740	5.61	1.42	***	0.07	0.20	ns	-	-	-	5.17	0.59	***	3.90	0.48	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 43. Linear regresaion coefficients, standard deviations, and statistical significances for unconfined compreasive strength data: Katy aeries.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance
Control DF = 9, r^2 = 0.260	-0.91	2.82	ns	-0.21	0.15	ns	-	-	-	-	-	-	-	-	-
Lime DF = 13, r^2 = 0.745	2.77	3.16	ns	-0.01	0.21	ns	4.59	0.91	***	-	-	-	-	-	-
PC3 DF = 42, r^2 = 0.587	0.46	0.49	ns	-0.22	0.06	***	-	-	-	-0.75	0.16	***	-	-	-
PC3-Lime DF = 64, r^2 = 0.609	-3.56	0.71	***	0.34	0.19	+	4.89	0.71	***	-0.89	0.43	*	-	-	-
PC3-Lime-Fly Ash DF = 87, r^2 = 0.727	-1.05	1.10	ns	0.29	0.25	ns	8.00	1.02	***	-1.28	0.66	+	8.71	1.05	***

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 44. Linear regression coefficients, standard deviations, and statistical significance for unconfined compreasive strength data: Upshur series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance	Regression Coefficient	Standard Deviation	Signifi-cance
Control DF = 2, r^2 = 0.897	0.16	1.54	ns	-0.34	0.11	+	-	-	-	-	-	-
Lime DF = 5, r^2 = 0.802	-1.08	1.21	ns	-0.22	0.07	*	-0.54	0.64	ns	-	-	-
FGl-Lime DF = 11, r^2 = 0.783	-8.35	1.76	***	0.05	0.11	ns	-1.25	1.22	ns	-1.27	0.42	*
AMD DF = 15, r^2 = 0.519	-2.70	1.15	*	0.01	0.14	ns	-	-	-	-0.28	0.93	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 45. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Fellowship series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime PSI/% L			Cement, PSI/% C			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% FA		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 3, r^2 = 0.200	5.50	2.69	ns	0.24	0.12	ns	-	-	-	-	-	-	-	-	-	-	-	-
Lime DF = 7, r^2 = 0.768	0.00	2.36	ns	0.05	0.10	ns	-1.63	0.38	**	-	-	-	-	-	-	-	-	-
Cement DF = 5, r^2 = 0.700	-8.77	5.07	ns	-0.35	0.23	nd	-	-	-	-0.99	2.09	ns	-	-	-	-	-	-
PCl DF = 14, r^2 = 0.183	-0.82	0.70	ns	-0.05	0.07	ns	-	-	-	-	-	-	-0.27	0.16	ns	-	-	-
PCl-Lime DF = 36, r^2 = 0.517	0.25	0.23	ns	-0.50	0.09	***	-1.47	0.47	**	-	-	-	0.02	0.23	ns	-	-	-
PCl-Lime-Fly Ash DF = 57, r^2 = 0.309	-0.44	0.27	ns	-0.46	0.10	***	0.63	0.51	ns	-	-	-	0.38	0.31	ns	-0.60	0.44	ns
PCl-Cement DF = 24, r^2 = 0.447	-4.96	2.22	*	-0.48	0.24	+	-	-	-	1.14	1.16	ns	-1.01	0.53	+	-	-	-

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 46. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Lake Charles series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 9, r^2 = 0.097	-1.20	2.66	ns	-0.11	0.11	ns	-	-	-
PG3 DF = 23, r^2 = 0.367	-3.08	1.35	*	0.19	0.10	+	-0.49	0.50	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 47. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Sharkey series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 2, r^2 = 0.872	3.56	0.97	+	0.00	0.01	ns	-	-	-	-	-	-
Lime DF = 6, r^2 = 0.935	0.58	1.37	ns	0.32	0.13	*	-3.86	0.83	**	-	-	-
PGl-Lime DF = 9, r^2 = 0.752	1.92	2.42	ns	0.42	0.21	+	-3.03	1.46	+	0.07	0.90	ns
PG3 DF = 16, r^2 = 0.366	-1.26	0.63	+	-0.02	0.10	ns	-	-	-	-0.16	0.32	ns
PG3-Lime DF = 35, r^2 = 0.248	0.62	1.52	ns	0.23	0.27	ns	1.08	1.07	ns	1.75	1.04	ns

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 48. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Sharpsburg series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW			Fly Ash, PSI/% KD		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 22, r^2 = 0.077	0.85	0.70	ns	-0.05	0.08	ns	-	-	-	-	-	-	-	-	-	-	-	-
Lime DF = 30, r^2 = 0.240	1.67	0.88	+	0.08	0.09	ns	-0.43	0.47	ns	-	-	-	-	-	-	-	-	-
Kiln Dust DF = 27, r^2 = 0.470	0.87	0.83	ns	-0.02	0.08	ns	-	-	-	2.12	0.52	***	-	-	-	-	-	-
PG2 DF = 36, r^2 = 0.749	0.54	0.53	ns	-0.06	0.05	ns	-	-	-	-	-	-	-1.41	0.23	***	-	-	-
PG2-Lime DF = 62, r^2 = 0.450	-4.33	1.96	*	0.59	0.21	**	3.11	1.07	**	-	-	-	2.10	0.81	*	-	-	-
PG2-Lime-Fly Ash DF = 84, r^2 = 0.485	-2.84	1.56	+	0.40	0.17	*	4.27	0.88	***	-	-	-	1.51	0.68	*	0.54	0.71	ns
PG3 DF = 36, r^2 = 0.186	-0.72	0.50	ns	-0.02	0.06	ns	-	-	-	-	-	-	-0.24	0.16	ns	-	-	-
PG3-Lime	-0.96	1.17	ns	0.29	0.15	+	1.78	0.69	*	-	-	-	0.18	0.42	ns	-	-	-
PG1-Lime DF = 56, r^2 = 0.128	1.17	0.70	ns	0.05	0.06	ns	-0.69	0.18	***	-	-	-	-0.29	0.19	ns	-	-	-
PG2 DF = 55, r^2 = 0.341	0.62	0.50	ns	-0.01	0.07	ns	-	-	-	-	-	-	-0.49	0.23	ns	-	-	-
PG2-Lime DF = 81, r^2 = 0.191	1.81	0.50	***	0.04	0.07	ns	0.26	0.43	ns	-	-	-	0.18	0.20	ns	-	-	-
PG2-Kiln Dust DF = 83, r^2 = 0.998	-3.16	0.06	***	0.06	0.01	***	-	-	-	4.45	0.02	***	-2.44	0.02	***	-	-	-
AMD DF = 36, r^2 = 0.539	0.52	0.50	ns	-0.03	0.05	ns	-	-	-	-	-	-	-1.01	0.26	***	-	-	-
AMD-Lime	2.23	0.60	***	0.12	0.06	*	-0.78	0.47	ns	-	-	-	-1.99	0.24	***			

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

Table 49. Linear regression coefficients, standard deviations, and statistical significances for unconfined compressive strength data: Summit series.

System	Moisture, PSI/% H_2O			Time, PSI/day			Lime, PSI/% L			Kiln Dust, PSI/% KD			Sulfate Waste, PSI/% SW		
	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance	Regression Coefficient	Standard Deviation	Significance
Control DF = 7, r^2 = 0.127	1.24	1.94	ns	-0.15	0.15	ns	-	-	-	-	-	-	-	-	-
Lime DF = 12, r^2 = 0.117	-0.92	2.22	ns	0.16	0.14	ns	-0.96	1.62	ns	-	-	-	-	-	-
Kiln Dust DF = 12, r^2 = 0.673	-2.19	2.59	ns	0.04	0.19	ns	-	-	-	2.08	1.28	ns	-	-	-
FG2 DF = 34, r^2 = 0.237	1.93	0.62	**	-0.01	0.09	ns	-	-	-	-	-	-	1.32	0.44	**
FG2-Lime DF = 54, r^2 = 0.130	0.50	0.64	ns	0.17	0.09	+	-0.75	0.67	ns	-	-	-	0.12	0.41	ns
FG2-Kiln Dust DF = 61, r^2 = 0.582	2.25	1.00	*	-0.03	0.18	ns	-	-	-	5.50	0.63	***	1.88	0.59	**

Key: DF = Degrees of freedom.
r^2 = Index of determination (square of correlation coefficient).
*** = Significant at 99.9% level.
** = Significant at 99% level.
* = Significant at 95% level.
+ = Significant at 90% level.
ns = Significance below 90% level.

1 psi = 6.9 kPa

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